Int. J. Environ. Res., 7(1):131-138, Winter 2013
ISSN: 1735-6865

Influence of Acoustic waves on Deposition and Coagulation of fine Particles

Noorpoor, A. R.[1*], Sadighzadeh, A.[2] and Habibnejad, H.[1]

[1] Graduate Faculty of Environment, University of Tehran, Tehran, Iran

[2] Air, Energy and Environment institute of university of Tehran, Tehran, Iran

Received 20 Jan. 2012; Revised 20 May 2012; Accepted 10 July 2012

ABSTRACT: The removal of fine particles less than 2.5 μm in diameter generated from industrial plants represents a serious challenge in air pollution abatement. These particles can penetrate deeply into the lungs and are difficult to remove by cyclones, electrostatic precipitators, and other conventional separation devices. In this paper, the influence of acoustic waves on removing aerosol particles from gas flue is studied. The mechanism of this effect includes the coagulation of nanometer particles to each other and forms larger particles. Moreover,these particles adhere to the wall of the test-rig pipe by the acoustic precipitation mechanism. Therefore, the particles are separated from the gas flue. Experiments are carried out on particle sized in the range of 260-3000 nm. Micro-sphere particles immersed in the air are subjected to homogeneous plane standing-waves at frequencies ranging from 100 Hz up to 2 kHz and a pressure level of 120 to 150 dB. At high pressure levels,the results indicate that the system has high efficiency for removing fine particles.

Key words: Aerosol,Coagulation, Particle, Acoustic,Wave

INTRODUCTION

Air quality degradation due to fine particles emission from industrialized and urban areas has been considered by lots of researchers during recent decades (Montero Lorenzo *et al.,* 2011; Cui *et al.,* 2011; Quesada-Rubio *et al.,* 2011; Zou *et al.,* 2011; Wang *et al.,* 2011; Nava-Martinez *et al.,* 2011; Jimenez *et al.,* 2011; Lee *et al.,* 2012; Fotouhi and Montazeri, 2012; Nejadkoorki and Baroutian, 2012; Katsura, 2012; Chianese *et al.,* 2012; Balabanova *et al.,* 2012; Ataei *et al.,* 2012; Barrera *et al.,* 2012). It is well known that a great portion of the ambient fine particles originating from combustion sources including fossil fuel power plants, cement kilns, and vehicle source conventional particle removal systems such as electrostatic precipitators and cyclones, do not have great efficiency in fine particles with sizes less than a micrometer (Wei and Teng, 1999). 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 (Timoshenko1965 and Liu, 2000). 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 (Gallego J. A. 1999, Riera-Franco de Sarabia, 2000, Moldavsky L. 2006). From 130 dB of acoustic pressure level, the turbulence condition is created in the experimental chamber (Sadighzadeh, 1990). At a pressure level higher than 150 dB, the media in the experimental chamber is totally turbulent. Above158 dB (this value corresponds to the great enhancement of acoustic turbulence) the agglomeration efficiency is strongly reinforced and a phenomenon of precipitation is observed. In turbulent conditions, depending on their dimensions, the aerosol particles are influenced by the forces provoked waves. Under high acoustic intensity, two extra mechanisms directly linked to the appearance of turbulence, are responsible for particle agglomeration. Inertial turbulent interactions are produced between particles of different inertia, which are more or less carried along the eddying motion. Diffusional turbulent interactions are produced between particles of the same size carried by two adjacent eddies (Chou, Lee and Shaw 1981). L. Hoffmann has studied the coagulation of aerosol particles in the range of 100 nm to 10000nm with the experimental conditions of 160 dB, 44 Hz and duration of 3 second. He observed, as an influence of acoustic waves, about 23% of the particle mass of all stages below 11 μm were moved into the size range above 11 μm, and for particles collected in the 2 μm stage, a

*Corresponding author E-mail: noorpoor@ut.ac.ir

reduction of about 50% of the mass was achieved (Hoffmann, 2003). This research evaluates the effect of acoustic waves on the increase of mean sizes of fine particles and compares the experimental results to the numerical model (Monte Carlo).This report deals with the study of using acoustic waves in order to increase particle sizes and to separate particles from gas.

There are two main mechanisms that describe acoustic agglomeration in the sound field; orthokinetic and hydrodynamic. Mednikov introduced the orthokinetic agglomeration process (Mednikov 1965, Temkin1994). In this mechanism, aerosol particles with various 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 (Donga 2006). 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 (Sheng and shen 2004). 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) (Riera 2006). 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 (Gonzalez 2003).

In acoustic wake mechanisms, particles interact through the surrounding fluid due to hydrodynamic forces and asymmetry of the flow field around each particle (Shaozeng 1996). 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 (Tiwary 1985,Hoffmann 1993).

MATERIALS & METHODS

For simulation of the agglomeration process in a typical agglomeration chamber, the DSMC (Direct Simulation Monte Carlo) method used with a finite volume V has been employed. The first assumption by the simulation model is that aerosol particles are spherical even after agglomeration takes place. The cell is taken as a micro-elemental volume (i.e. simulated volume), representing a subsystem at any location of the agglomeration chamber. This volume contains a suspension of N (initially, N_0) spherical particles with an initial size distribution. The second assumption by the model is that the both fill-up efficiency and adhesion efficiency equal unit. Further assumptions by the model are that particle concentration and acoustic velocity are uniform at any cross section of the agglomeration chamber. Periodic boundary conditions are assumed for the cell, i.e. particles moving out of the simulated volume are replaced immediately by identical particles moving in. The particle and acoustic properties (e.g., particle concentration and size distribution, acoustic frequency and intensity, etc.) in the simulated volume can be changed to account for the variations of these properties due to many factors in the practical processes, such as particle dispersion and deposition, turbulent flow, boundary conditions, sound attenuation, etc. In this simulation, the aerosol system is considered as a homogeneous suspension of particles in the air at room temperature (300 K) and atmospheric pressure. The last assumption is that the relative diffusion rate between particles enhanced by the acoustic waves is negligible in comparison to impaction and interception rates. This may be true when acoustic intensity is high and particle sizes are not too small. Nevertheless, the use of this assumption in the model tends to underestimate the agglomeration of very fine particle. The system is assumed to be static, with travelling wave acting on it so as to avoid dealing with the turbulence effects and complex boundary conditions. Nevertheless, it can be easily extended to cover these effects. For a fractal-like aggregate, its equivalent size is generally defined according to the well-known exponent law:

$$N_p = A\left(\frac{r}{r_0}\right)^{D_f} \tag{1}$$

The pre-factor A in Equation 1 depends on the definition of the diameter and the fractal dimension. It is generally close to 1. Therefore, it was taken as 1 in many numerical studies. In the present work, A is also simply set to 1 while the research interest is focused on the effect of the fractal dimension.Where N_p is Number of the primary particles in the aggregate, r_0 and r are the Radius of the primary and aggregate particles. In the acoustic agglomeration system, particles collide and consequently agglomerate due to their relative motion mainly induced by the sound wave. Assuming that the collisions are binary, all collisions lead to agglomeration, and while only the agglomeration occurs in the system, the evolution of the particle number with time can be described by the classic Smoluchowski equation:

$$\frac{\partial n_k}{\partial t} = \frac{1}{2}\sum_{i=1}^{k-1}\beta_{i,k-1}n_i n_{k-1} - n_k \sum_{i=1}^{\infty}\beta_{i,k}n_i \qquad (2)$$

Where $\beta_{i,k}$ refer to Collision rate or the agglomeration frequency function(also called the agglomeration kernel) of the particle pair (i and k), n_i: particle number concentration and its series(here i) in the aerosol

In the DSMC method, the particle pairs are selected by stochastic games based on the collision probabilities transformed from the collision rates. As a result, the time evolution of the particle number and particle properties such as the particle size is represented by directly simulating the collision/ agglomeration of particle pairs in the simulated volume rather than by solving Equation (2). To formulate the agglomeration kernel, the additive of the contributions from the orthokinetic and hydrodynamic agglomerations as well as from Brownian coagulation is taken into account. Following Song (1990) (Song 1990), the orthokinetic kernel is expressed as:

$$\beta^{Or} = 2(r_1 + r_2)^2 U_0 \eta_{s12} \qquad (3)$$

The hydrodynamic agglomeration is driven by the hydrodynamic force in the fluid due to two particles coming close to each other. In ideal fluid, the hydrodynamic agglomeration frequency function can be described by the classic expression of Konig:

$$\beta^{Hy} = \frac{\sqrt{3}\rho_0 U_0^2}{9\mu}\frac{r_1^2 r_2^2}{r_1 + r_2} \qquad (4)$$

As for the Brownian coagulation, the kernel, considering the coagulation in the near-continuum regime with the Cunningham correction, is written as:

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

K is Boltzmann constant and C_1 and C_2 are Cunningham correction factors for the two aggregates respectively, which are dependent on the particle Knudsen numbers. Here:

$$c = 1 + k_n\left[a_1 + a_2 \exp\left(\frac{-a_3}{k_n}\right)\right] \qquad (6)$$

Where the constants a_1, a_2 and a_3 are taken as 1.142, 0.558 and 0.999, respectively, following (Allen and Raabe 1985) and the Knudsen number *K*n is defined as $Kn = 2\lambda/d$ using the mean molecular free path of air, λ and the particle diameter, d

The particle agglomeration in an acoustic wave actually results from the combined contributions of all mechanisms involved in the process, including the orthokinetic and hydrodynamic mechanisms and etc. A linear combination or a simple addition of the agglomeration kernels was often assumed to calculate the overall agglomeration rate. In the present work, the simple additive method is applied, i.e.

$$\beta = \beta^{Or} + \beta^{Hy} + \beta^B \qquad (7)$$

In modeling, Eq (7) is used for the simulation of acoustic agglomeration.

The experimental test-rig and apparatus is shown in Fig. 1. The experimental test setup basically consists of an aerosol generator, a cascade impactor, a particle counter, an acoustic agglomeration–precipitation chamber and a sound source. It is set up on the inside of a glass column with a 160*cm* height and 6.3*cm* internal diameter. The mono-disperse and poly-disperse aerosols of D.O.P (C_6H_4 ($COOCH_2CH$ (C_2H_5) C4H9)) used in our experiment are produced by two aerosol generator devices (T.S.I. model 3475and GRIMM model 78225). The acoustic waves are generated by a high power loud-speaker (50 watts). The sinusoidal signal is fed by a signal generator which is amplified first by an audio-amplifier before it is fed to a loud speaker.A system of dilution allows us to produce aerosol concentrations at a scale of 10^6 particles per cm^3. The flow air is assured by an air pump.The experiment is performed at room temperature and pressure.

RESULTS & DISCUSSION

The acoustic coagulation and precipitation rate in our set-up was measured for the frequencies of 200, 650and 830 Hz and also a variation of intensity from 120 to 145 dB. These frequencies correspond to the resonance frequencies of the used system. The coagulation and precipitation efficiency of the system were studied with fine (260 nm) and large (2000 nm) particles. The particle concentration used is 10^6 particles per cm^3 and the electrical power is set at 27 Watts. This supply is at a maximum145 dB of intensity (pressure level) in the system. The coagulation ratein

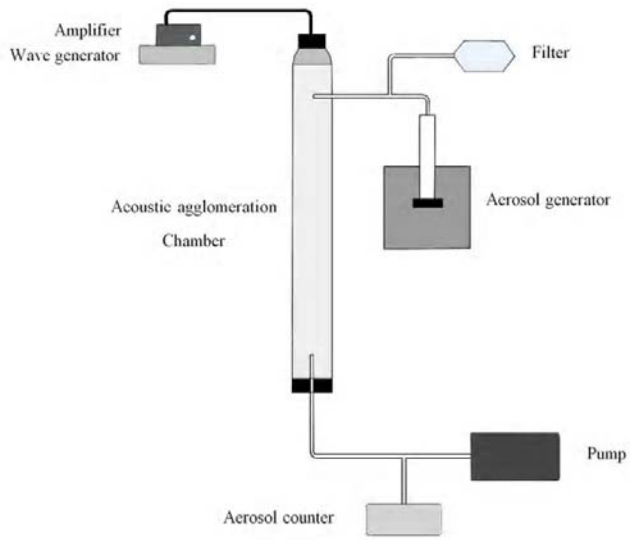

Fig. 1. Schematic of experimental set-up

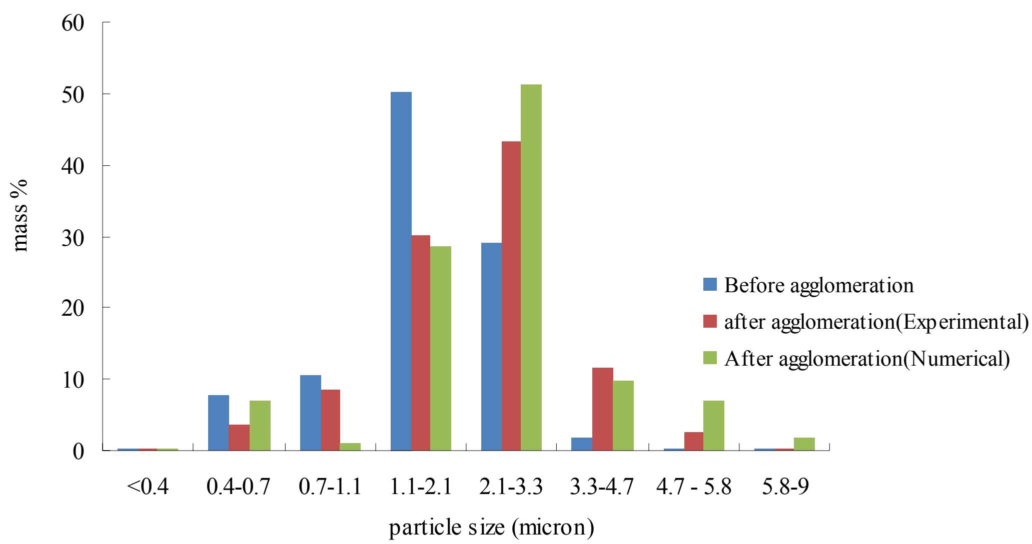

Fig. 2. Agglomeration test on closed chamber withmono disperse (2 micron) aerosol, f=200Hz, P=27 Watt, Q=0

the system with 2000 nm particles is determined (Fig. 2) in presence of the acoustic wave (200Hz, 138 dB). The application of acoustic wave time is fixed at 60 seconds. As it is shown, the mass percentage of large particles increased under sound pressure. For example, the particles in the range of 1.1 - 2.1µm transform from 53% to 31% and the mass percentage of particlesin the range of 3.3 to 4.7µm which was initially 2% increased to 12%. Numerical modeling results presented in Fig. 2 shows a practically good agreement with experimental data.

In practice the efficiency of a removal system is determined by:

$E=1–N_f/N_i$(8)

The efficiency of the system is studied for elimination of aerosol particles. The frequencies used are 650 Hz and 830 Hz with intensities of 143 dB and 145dB, respectively (Fig. 3). It has been observed that the acoustic precipitation efficiency is near 100%. Indeed, particles in the chamber are coagulated and adhere to the chamber wall. The place in which particles adhere to the rim is normal and depends on the wave length. In our investigation, the acoustic precipitationrate is measured with an air flow fixed at *1698 lit/hour and 250lit/hour*. The frequency and sound pressure level used are 830 Hz and 145 dB, respectively. The result of this investigation is shown as mass granulometric variation (Fig. 4).The removal efficiency of the system is high, for example it attends to near 100% and 91% for the particles in the range of 2.1-4.7 µm diameter size, with a flow rate of 250 L/h and 1698 L/h, respectively. In fact, with increasing air flow, the residence time of particles in the chamber decreases and as a result, they expose less time to high intensity acoustic waves. In this process the probability of particle collision with other particles and with the chamber rim is reduced. As a result, the efficiency of particle removal in the acoustic precipitator is decreased.The removal efficiency of the system for the fine particles (<1000 nm) are studied. The frequency and sound intensity are fixed at 830 Hz and 145 dB, respectively. The particle sizes used in this investigation are 260nm in diameter. Our experimental

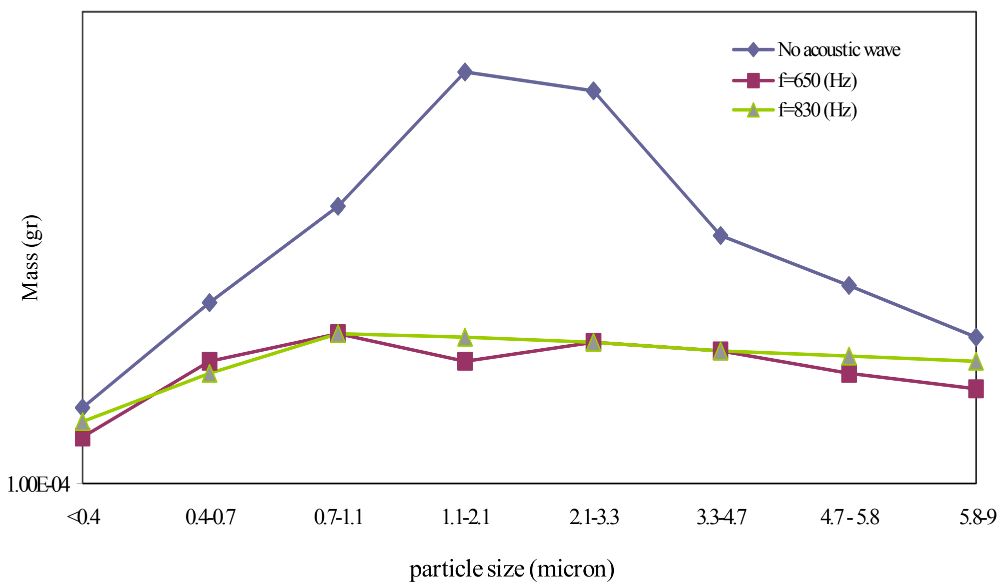

Fig. 3. Agglomeration test on closed chamber with mono disperse (2 micron) aerosol, f=650, 830Hz, P=27 Watt, Q=0

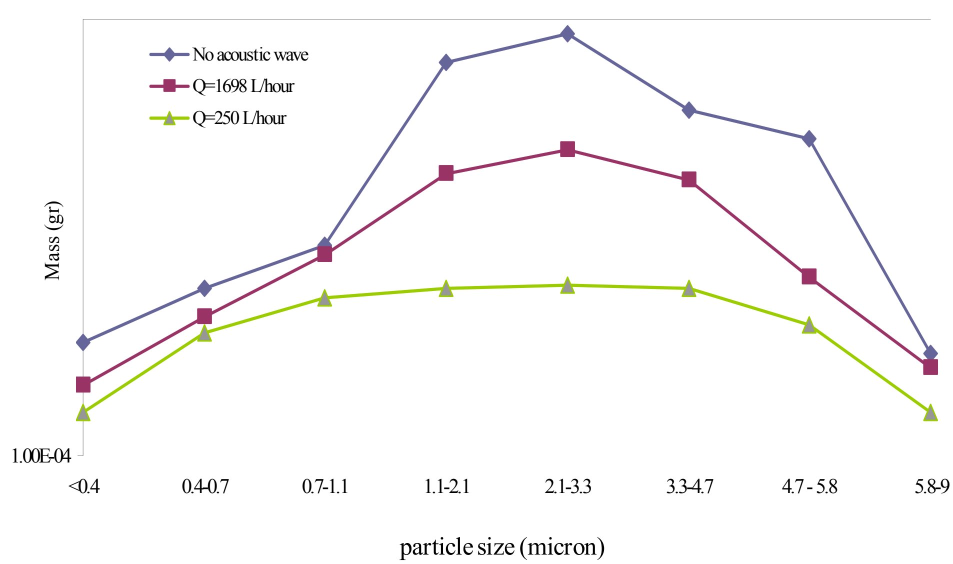

Fig. 4. Acoustic precipitation rate

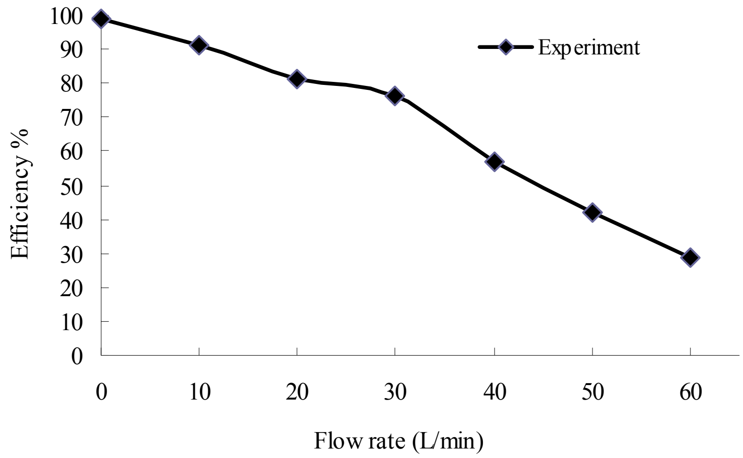

Fig. 5. Influence of flow rate on acoustic removal efficiency

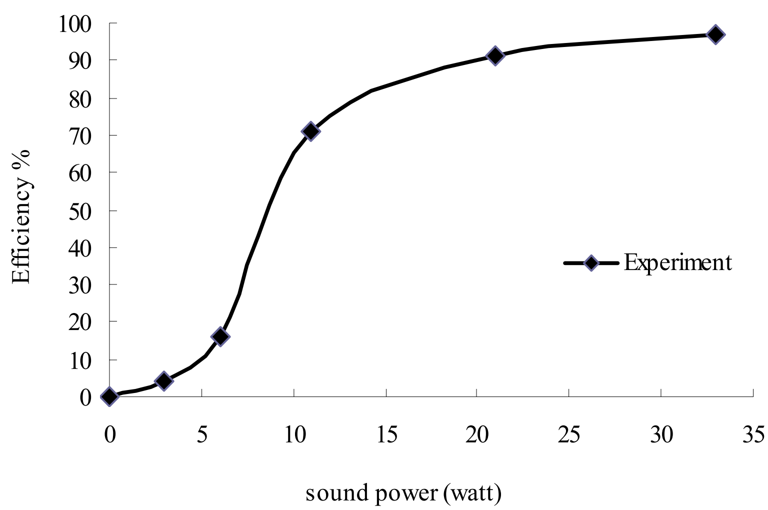

Fig. 6. Influence of sound power on acoustic removal efficiency

data show an important efficiency (93.35%) with the low flow rate 10 L/min (fig.5). The efficiency decreases with the increase in air flow. For example, at a flow rate of 50 L/min, the acoustic precipitator efficiency equals to 43.2%.

In fig. 6, the influence of electrical sound power on the removal efficiency of the system is shown. Experiments on the influence of sound power are carried out in f=830 Hz and Q=30 lit/min. Our results show that the removal efficiency increases with the rise in electric power supplied to the speaker. This increase is very fast for above 3 watts. It is supposed that the turbulence condition is created for power higher than 3 watts.

CONCLUSIONS

In this work, the influence of acoustic waves on removing nanometric particles larger than 1 micron from an aerosol gas system under coagulation and precipitation effect is investigated. The experiment results show that the acoustic wave with appropriate intensity and frequency can remove particles from the gas flue with high efficiency. These studies show that the high efficiency of particle removal can be carried out even with a low flow rate.

REFERENCES

Allen, M. D. and Raabe, O. G. (1985). Slip correction measurements of spherical solid aerosol particles in an improved Millikan apparatus. Aerosol Science and Technology, **4**, 269–286.

Ataei, A., Iranmanesh, A. and Rashidi, Z. (2012). Life Cycle Assessment of Advanced Zero Emission Combined Cycle Power Plants, Int. J. Environ. Res., **6 (3)**, 801-814.

Balabanova, B., Stafilov, T., Šajn, R. and Baèeva, K. (2012). Characterisation of Heavy Metals in Lichen Species Hypogymnia physodes and Evernia prunastri due to Biomonitoring of Air Pollution in the Vicinity of Copper Mine. Int. J. Environ. Res., **6 (3)**, 779-794.

Barrera, V. A., Miranda, J., Espinosa, A. A., Meinguer, J., Martínez, J. N., Cerón, E., Morales, J. R., Miranda, P. A. and Dias, J. F. (2012). Contribution of Soil, Sulfate, and Biomass Burning Sources to the Elemental Composition of PM10 from Mexico City. Int. J. Environ. Res., **6 (3)**, 597-612.

Chianese, E., Riccio, A., Duro, I., Trifuoggi, M., Iovino, P., Capasso, S. and Barone, G. (2012). Measurements for indoor air quality assessment at the Capodimonte Museum in Naples (Italy). Int. J. Environ. Res., **6 (2)**, 509-518.

Chou, K. H., Lee, P. S. and Shaw, D. T. (1981). Aerosol agglomeration in high-intensity acoustic fields Laboratory for Power and Environmental Studies, State University of New York, Buffalo, New York, 14226 USA.

Cui, H . Z ., Sham, F. C., Lo, T. Y. and Lum, H. T. (2011). Appraisal of Alternative Building Materials for Reduction of CO2 Emissions by Case Modeling. Int. J. Environ. Res., **5 (1)**, 93-100.

Fotouhi, A. and Montazeri, Gh. M. (2012). An Investigation on Vehicle's Fuel consumption and Exhaust Emissions in Different Driving Conditions. Int. J. Environ. Res., **6 (1)**, 61-70.

Gallego, J. A., Riera, E., Elvira, L., Rodrfguez, G., Vizquez, F., Hoffmann, T. L. and Montoya, F. (1995). Acoustic Preconditioning of Coal Combustion Fumes for Enhancement of Electrostatic Precipitator Performance. The Acoustic Preconditioning System Elsevier Science B.V.

Gonzalez, I., Juan, A., Gallego, J. and Riera, E. (2003). The influence of entrainment on acoustically induced interactions between aerosol particles an experimental study Instituto de Acustica, CSIC, Calle Serrano 144, 28006 Madrid. Spain Aerosol Science, **34**, 1611–1631.

Hoffmann, T. L. (1993).Visualization of particle interaction and agglomeration in an acoustic field, Ph.D Dissertation, USA.

Hoffmann, T. L. (2000). Environmental implication of acoustic aerosol agglomeration, Ultrasonics, **38**, 353-357.

Hoffmann, T. L. (2003). Environmental implications of acoustic aerosol agglomeration, J. Ultrasonics, USA.

Jimenez, L., Mateo, J. M., Lopez-Arevalo, I. and Oms, M. T. (2011). Operational Predictive Model for a Municipal Waste Incinerator: A Spanish Case Study. Int. J. Environ. Res., **5 (3)**, 639-650.

Katsura, H. (2012). The Effect of Electrically Charged Clouds on the Stable Nitrogen Isotope Ratio and the Anion Concentrations in Cloud-based Aerosols. Int. J. Environ. Res., **6 (2)**, 457-466.

Lee, J. G., Lee, K. H., Choi, H. I., Moon, H.I. and Byeon, S. H. (2012). Total Dust and Asbestos Concentrations during Asbestos-Containing Materials Abatement in Korea. Int. J. Environ. Res., **6 (4)**, 849-852.

Mednikov, E. P. (1965). Acoustic agglomeration and precipitation of aerosols, J. Aerosol Science, New York.

Moldavsky, L., Fichman, M. and Gutfinger, C. (2006). Enhancing the performance of fibrous filters by means ofacoustic waves AerosolScience, **37**, 528–539.

Montero Lorenzo, J. M., Garcia-Centeno, M. C. and Fernandez-Aviles, G. (2011). A Threshold Autoregressive Asymmetric Stochastic Volatility Strategy to Alert of Violations of the Air Quality Standards. Int. J. Environ. Res., **5 (1)**, 23-32.

Nava-Martinez, E. C., Garcia-Flores E. and Wakida F. T. (2011). Surface Methane Emission in a Former Dumpsite in Tijuana, Mexico. Int. J. Environ. Res., **5 (3)**, 621-626.

Nejadkoorki, F. and Baroutian, S. (2012). Forecasting Extreme PM10 Concentrations Using Artificial Neural Networks. Int. J. Environ. Res., **6 (1)**, 277-284.

Quesada-Rubio, J. M., Villar-Rubio, E., Mondéjar-Jiménez, J. and Molina-Moreno, V. (2011). Carbon Dioxide Emissions vs. Allocation Rights: Spanish Case Analysis. Int. J. Environ. Res., **5 (2)**, 469-474.

Riera-Franco de Sarabia, E., Gallego-Jua´rez, J.A., Rodrý´guez-Corral, G. Elvira-Segura L. and Gonza´lez-Go´mez. I. (2000). Application of high-power ultrasound to enhance fluid/solid particle separation processes, J. Ultrasonics, Spain.

Riera, Enrique., Juan, A., Gallego-Jua´rez. and Mason Timothy, J. (2006). Airborne ultrasound for the precipitation of smokes and powders and the destruction of foams, UK Ultrasonics Sonochemistry, **13**, 107–116.

Song, L. (1990). Modeling of acoustic agglomeration of aerosol particles, Ph.D Dissertation, USA.

Sadighzadeh, A. (1990). Etude de l'efficacite de capitation des aerosol par un lit granulaire en l'absence et en presence d'ondesacoustiques, Ph.D. Dissertation, FRANCE.

Shaozeng, D., Lipkensb, B. and Cameronc, T. M. (2006). The effects of orthokinetic collision, acoustic wake, and gravity on acoustic agglomeration of polydisperse aerosols, USA Aerosol Science, **37**, 540–553.

Shaozeng, D. (1996). Investigation of orthokinetic and acoustic wake effect for acoustic agglomeration of flyash aerosols, PhD dissertation, Shanghai University, Shanghai, China.

Sheng, C. and Shen, X. (2004). Modelling of acoustic agglomeration processes using the direct simulation Monte Carlo method, J. Aerosol Science, China.

Timoshenko, V. I. (1965). Investigation ofthe interaction betwin aerosol particles in an acoustic field, Leningrad Eng Tech Ins.

Tiwary, R. (1985). Acoustic Agglomeration of Micron and Submicron Fly Ash and aerosol, Ph.D dissertation, the Pennsylvania state.

Temkin, S. (1994). Gasdynamic agglomeration of aerosols. I. Acoustic waves. Physics of Fluids, **6**, 2294–2303.

Wang, P., Zhao, D., Wang, W., Mu, H., Cai, G. and Liao, C. (2011). Thermal Effect on Pollutant Dispersion in an Urban Street Canyon. Int. J. Environ. Res., **5 (3)**, 813-820.

Wei, F., Teng, E., Wu, G., Hu, W., Wilson, W. E., Chapman, R. S., Pau, J. C. and Zhang, J. (1999). Ambient concentrations and elemental compositions of PM_{10} and $PM_{2.5}$ in four Chinese cities. Environment. Sci. Technol., **33**, 4188–4193.

Zou, B., Zhan, F. B., Zeng, Y., Yorke, Ch. and Liu, X. (2011). Performance of Kriging and EWPM for Relative Air Pollution Exposure Risk Assessment, Int. J. Environ. Res., **5 (3)**, 769-778.