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APPLICATION OF THE ACOUSTIC AGGLOMERATION TO REDUCE FINE PARTICLE EMISSIONS IN COAL COMBUSTION PLANTS

JUAN A. GALLEGO-JUÁREZ*, ENRIQUE RIERA-FRANCO DE SARABIA, GERMAN RODRÍGUEZ-CORRAL, THOMAS L. HOFFMANN# AND JUAN C. GÁLVEZ-MORALEDA

Instituto de Acústica, CSIC, Serrano 144, 28006 Madrid, Spain

JESUS J. RODRÍGUEZ-MAROTO, FRANCISCO J. GÓMEZ-MORENO, ALBERTO BAHILLO MANUEL AND MANUEL MARTÍN-ESPIGARES

CIEMAT, Av. Complutense 22, 28040 Madrid, Spain

MIGUEL ACHA

ASINEL, Apartado 233-28930 Móstoles (Madrid), Spain

ABSTRACT

Removal of fine particles (smaller than 2.5 microns) from industrial flue gases is, at present, one of the most important problems in air pollution abatement. These particles, which are the most dangerous because of their ability to penetrate in lung tissue, are difficult to remove by conventional separation technology.

Sonic energy offers a means to solve the problem. The application of a high intensity acoustic field to an aerosol induces an agglomeration process which changes the size distribution in favor of larger particles, which are then more easily precipitated by a conventional separator. In this work, we present a semi-industrial pilot plant in which this process is applied for reduction of particle emissions in coal combustion fumes. This installation basically consists of a rectangular-section acoustic agglomeration chamber driven by four high power and high directional acoustic

* tel: 34-91.561.88.06, fax: 34-91.411.76.51, e-mail: jgallego@fresno.csic.es

transducers of 10 and/or 20kHz and an electrostatic precipitator (ESP). The fume generator is a fluidized bed coal combustor. A special sampling and measuring station was set up. Experiments were carried out with fume flow rates up to about 2000 Nm^3/h, gas temperatures of about 150ºC and mass concentrations in the range 1-5 g/Nm^3. The fine particle reduction produced by the acoustic filter is of about 40 % of the number concentration.

present address Fraunhofer Technology Center Hialeah, 601 W 20th Street, Hialeah, Florida 33010, USA

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CIEMAT, Av. Complutense 22, 28040 Madrid, Spain

MIGUEL ACHA

ASINEL, Apartado 233-28930 Móstoles (Madrid), Spain

Keywords: acoustic particle agglomeration, acoustic preconditioning, particle characterization, filtration, flue gas cleaning, electrostatic precipitator

Introduction

Removal of fine particles smaller than 2.5 microns from industrial flue gases is one of the most important problems in the protection of the atmosphere from air pollution. In fact, these particles constitute a major health hazard because of their ability to penetrate into respiratory tissue. In addition, they are generally toxic due to either their origin (condensation of chemically active elements produced during combustion processes) or to their capability to act as a vehicle for noxious agents (e.g. viruses, bacteria, dioxin). Therefore, a renewed interest is presently shown in the control of fine particle emission from industrial combustion plants and a

[#] present address Fraunhofer Technology Center Hialeah, 601 W 20th Street, Hialeah, Florida 33010, USA

new legislation, more stringent about them is now being introduced (1). Fine particles make up a relevant percentage of the particulate emission in coal burning processes (such as coal fired power plants) in steel-melting industry (open-hearth and converter), and in the cement industry. At the same time, conventional filters to remove particulate, such as electrostatic precipitators (ESPs) drop of steeply in retention efficiency for the particles under 2 or 3 microns (2). As a consequence, an improved technology will be necessary to obtain higher fine-particle retention efficiencies.

Agglomeration of micron and submicron particles to form larger particles seems to be a promising process to precondition the particles before entering into a conventional filter in order to increase its collection efficiency. Particle agglomeration by means of acoustic and electric fields has been investigated.

Agglomeration studies and experiments by using alternating electric fields have been recently carried out by Eliasson et al (3), Gutsch and Löffler (4) and Kildesϕ et al (5). The principle is to split the particle flow in two different flows, charge the particles of each flow oppositely and mix the charged particles in a single flow. The problem seems to be the difficulty in charging the tiny particles, which is just the limitation of the electrostatic precipitators. Nevertheless some authors claim results which can be considering as promising.

Acoustic agglomeration is another procedure to be considered. High intensity acoustic fields applied to an aerosol may induce interaction effects among suspended particles giving rise to collisions and agglomerations. The principle of acoustic agglomeration is mainly based on the relative motion produced between suspended particles of different size which promote particle collisions (orthokinetic effect) (6). Also, same-sized particles can agglomerate due to the action of hydrodynamic forces resulting from mutual distortion of the field around the particles (hydrodynamic effects) (7).

Acoustic agglomeration has been widely studied but the development of this process toward industrial application have been slow. This is probably because of the lack of suitable high intensity, high efficiency powerful sound sources and the corresponding full scale agglomeration equipment. We have been working for many years to overcome these problems (12-14). This paper presents the characteristics and performance of a new pilot scale, multifrequency acoustic agglomerator which has been tested in connection with an electrostatic precipitator for the treatment of fumes from a 0.5 MW_t fluidized bed coal combustor. The main novelty of this agglomerator is the use of a new type of macrosonic generator (15) which implements high power capacity, efficiency and directivity and permits the treatments of large volumes. Complementary, the acoustic chamber is designed to optimize the spatial homogeneity and intensity of the acoustic field distribution. In addition, the new agglomerator is able to apply different frequencies along the treatment path of the fume, which represents an important advance because the frequency of the sound field is linked to the particle size which is changing during the process. Finally, the chamber dimensions are determined by the residence time and the flow rate of the aerosol to be treated.

The agglomerator has been studied in terms of its acoustic characteristics and its performance to increase the retention efficiency of an electrostatic filter was evaluated by means of a sampling station set up to measure particle mass and number concentration and distribution.

Experimental Facility

The experimental facility consists basically of a circulating fluidized bed combustion plant (0.5 MW_t), a conventional electrostatic precipitator (ESP) and the acoustic agglomeration chamber. All these parts are coupled through a pipe line where the test aerosols are controlled and measured (Figure 1). The facility includes three sampling points (SPs) along the pipe line: SP1 upstream the acoustic chamber, SP2 between the acoustic chamber and the ESP and SP3

downstream the ESP. A mobile sampling station permits to perform a complete characterization of the aerosols along the process line. The acoustic agglomeration chamber has a length of 3.56 m and a rectangular cross-section of 0.7 x 0.5 m. Four specially designed stepped-plate, high-intensity transducers (two of 10kHz and another two of 20kHz) are arranged alongside the elongated agglomeration chamber to achieve a homogeneous distribution of the sound field as well as sufficient residence time of the aerosol in the chamber (2-3 sec.). The ESP main characteristics are shown in Table 1. Fume emission from combustion plant (approx. 140 Nm^3/h) was diluted with air previously heated in a propane burner to reach a total flow rate of approximately 1600 Nm^3/h. The diluted fume is treated in the acoustic agglomeration chamber previously to enter in the ESP. A scrubber is placed downstream the ESP as an absolute filter for environmental safety.

Requirements for Efficient Acoustic Preconditioning.

To achieve a satisfactory shift of the particle size distribution, macrosonic fields have to be employed. Previous theoretical and experimental studies show that for the applied sound pressure levels (SPL) the general rule “more-is-always-better” holds almost without constrain. For this reason, powerful sound sources for the treatment of large volumes at high sound pressure levels are indispensable for an efficient acoustic preconditioning system. Another important factor which strongly influences the resulting sound field patterns is the geometry of the agglomeration chamber. Here special attention has to be given to optimize for largest possible homogeneity and maximum spatial mean level within the chamber. Moreover, the frequency of the exciting sound field determines in which particle size range the preconditioning works most efficiently. Whereas frequencies of the higher audible range favor the agglomeration of micron sized particles, lower ultrasonic frequencies deliver better results

in the submicron range. Therefore, the sound frequency has to be adjusted in such a way that the performance of the acoustic preconditioning process is optimized with respect to a given aerosol size distribution. This becomes especially important when bimodal or multimodal size distributions are considered (as apparent in many fly ash distributions after coal combustion). The efficiency of the agglomeration process is also influenced by parameters such as temperature and pressure, residence time in the agglomerator, and aerosol concentration. Experiments show that the latter two quantities are crucial for efficient acoustic preconditioning (12,13)

Characteristics of the Acoustic Agglomeration Chamber

High-Power Transducers. Two different models of stepped-plate transducers permit the operation of the acoustic preconditioner at sonic (10 kHz), ultrasonic (20 kHz), or mixed frequencies (10 and 20 kHz) (see Figure 2). The extensively radiating plate of these transducers is used to increase the radiation impedance and the power capacity. Also, the directivity is controlled by the steps of the plate. In this application, we worked with axisymmetrically vibrating stepped-plates with five and seven nodal circles for 10 and 20 kHz and diameters from 48 to 67 cm. Transducers have beamwidths of 1.5º at 3 dB, radiation efficiencies of about 80%, and power capacities of about 1 kW. The electronic driving system was designed to operate continuously at the resonant frequency of the transducer. The device is based on analog type oscillator assembly, formed by a power amplifier which is refed by the transducer itself by means of a tuned bridge circuit, a phase shifter, and a band pass filter (15). Heating problems of the transducer radiating surfaces due to the high temperatures of the gas flow were avoided through an air cooling system in which an air layer between the radiators

and the fume flow provides a temperature gradient between the transducer surface and the flow itself (14).

Acoustic Characteristics of the System. A high intensity acoustic standing wave field was established within the agglomeration chamber to get a good balance between the stored energy and the volume of aerosol to be treated.

The acoustic field inside the agglomerator was studied in the laboratory in a model chamber made of pvc-glass having the same dimensions as the actual chamber. As shown in Figure 3, the transducers were located at the bottom of the chamber to generate an intense acoustic standing wave field perpendicular to the gas flow. The dimensions of the section of the chamber were chosen to keep the treated gas flow within the near field of the transducers. Figure 4 shows the profile of the spatial mean sound pressure level (SPL) generated by four transducers operating over the total length of the chamber as a multifrequency system (10 and 20 kHz) with an applied input power on each transducer of 400W. The maximum SPLs measured were higher than 165 dB and the minimum values were always above 145 dB. These levels are sufficient for efficient acoustic agglomeration.

Sampling Station

A particle sampling and measurement system was set-up in order to characterize suspended particles in the combustion gases. The system was able to give on-line data about number concentrations and size distributions, for micron and submicron ranges. In addition, mass concentrations and size distribution, particle morphology and chemical composition were obtained. Figure 5 shows schematically this sampling station (12,13). The aerosol is extracted from the duct and conducted to the sampling station through an isokinetic probe equipped with an automatic control unit. The sample could be diluted with dry filtered air to avoid

overloading of the measuring devices. Several instruments are used to perform simultaneous measurements covering the whole size range of the aerosol.

An on-line optical particle sizer based on white light scattering by single particles was used (18). This instrument provides number concentration and size distributions in the range 0.3-30 μm with a maximum allowable particle number concentration of 10^5 particles/cm^3.

Part of the diluted sample is split into four flows using an isokinetic flow splitter. These flows are conducted to different measuring instruments.

Information on number concentration and size distribution of particles in the submicron size range (0.005-0.5 μm) is obtained by using a Scanning Mobility Particle Sizer (SMPS) formed by a differential electrical mobility analyzer (19) coupled with a condensation nuclei counter. Because of limitations posed by this instrument, the sample must be preconditioned before entering the SMPS. A cyclone and a preimpactor remove the particles bigger than one micron before it. Then the sample is drawn into a chamber from which a suitable amount of sample is taken and conducted to the SMPS. This is necessary because usual sampling flowrates are much bigger than the maximum flowrate allowable by the SMPS.

A special device was designed to collect samples of particles deposited on glass coupons. The coupons are supported inside a cylindrical chamber into which the aerosol sample is drawn. Particles are deposited on the coupons by impaction, sedimentation and diffusion and the samples are later analyzed with Scanning Electron Microscopy (SEM). Information on morphology and size distribution can be obtained by image analysis and the elemental composition of particles can be determined by electron probe X-ray microanalysis (EPXMA).

Aerodynamic size distribution is determined using an eight stage cascade impactor (16) arranged with glass fiber paper substrates and backup filter. Additionally, 47 mm glass fiber paper filters are used to measure total mass concentration of the aerosol. Filters and substrates used can be chemically analyzed with different techniques such as: Atomic Absorption

Spectrometry (AAS); Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) (20).

The flow rate through the different sampling instruments is controlled and measured by using needle valves and mass flowmeters. After passing through the measuring and sampling devices the whole aerosol sample is filtered and drawn through the flow rate control unit, which adjusts and monitors it to achieve isokinetic sampling conditions (21). It was possible to compare the results of the different instruments and to see the correlation between them within the range in which each one is valid.

Results and Discussion

Some previous characterization tests were done in order to verify the performance of the combustion plant and the sampling and measurement station. These included the measurements of the mass and number particle size distribution and concentration and let us to compare the results of the different instruments among them within the range each one is valid (21).

Once the different systems were all working properly, the performance of the agglomeration-retention process was studied. The test matrix carried out under different operating conditions of the acoustic agglomeration chamber can be found in Table 2. During the experiments, the aerosol was characterized only at the sampling point SP3.

A brief summary of the results obtained with the acoustic chamber is shown in Table 3. In this table, the mass reduction means the particle mass percentage which is now retained by the ESP when the acoustic chamber is on, with respect to the particle emission when the acoustic chamber is off. It is also included the reduction of the particle number concentrations for the micron and submicron ranges as they were measured by the optical sizer and the SMPS. These results are graphically shown in Figure 6 where it is possible to see that the experiments performed with 20 kHz (Fig. 6b) have a slightly better result than those with 10 kHz (Fig. 6a).

The three bars refer to the application of four transducers with 400 W (4T 400W), two transducers with 200 W (2T 200W) and four transducers with 80 W (4T 80 W).

The evolution of the particle size distributions with the frequency and the power applied can be found in Figure 7 for the case of four transducers. The micron particles have a higher number concentration than the submicron particles because the combustion is in a fluidized bed. It appears very clear how the peak height decreases when the chamber is on and how this decrease is bigger for the maximum power applied for both frequencies studied. The improvement in the emission reduction when the acoustic filter works at its maximum power and frequency (4T x 400 W and 20 kHz) can reach values of up to 37 and 40 % of the mass and number concentration respectively, over the efficiency of the electrostatic filter. This can be considered a significant improvement particularly bearing in mind the very small size of the particles, the narrow gain margin let by the electrostatic filter, the low level of energy applied and the very short treatment time.

The new system presents several advantages. It may be applied to any industrial process where fine particles are produced. The preconditioning procedure is equally useful for any other filtering system such as cyclone filters, bag houses, or ceramic filters. Another important benefit of this process is its applicability in high-pressure and high-temperature environments (e.g. for coal gasification).

Finally, the prospects for large scale applications are very positive. Presently large transducers with power capacities of about 6kW are under development together with agglomeration chambers for the treatment of flow rates higher than 10000 m^3/h.

Acknowledgments

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TABLE 1

ESP main characteristics

Number of mechanical fields in series	2	Inlet voltage	380 V
Number of electrical fields	1	Inlet current	4 A
Total active length	3.0 m	Current frequency	50 Hz
Number of streets	4	Outlet voltage	35 kV
Street width	200 mm	Outlet current	25 mA
Projected precipitation surface	33.6 m^2		

TABLE 2

Test matrix. During all the experiments, the ESP voltage was fixed in 30 kV.

Test	**Number of transducers**	**Power per transducer (W)**	**Frequency (kHz)**
1	4	400	10
2	2	400	10
3	4	80	10
4	4	400	20
5	2	400	20
6	4	80	20

TABLE 3

Summary of results

Test	Mass Reduction (%)	Particle Number Reduction (%)	
		Micron	Submicron
1	32	37	39
2	29	33	21
3	26	26	16
4	37	42	39
5	29	31	31
6	24	14	24

FIGURE CAPTIONS

Figure 1. A general scheme of the experimental facility.

Figure 2. Macrosonic stepped radiator.

Figure 3. Acoustic agglomeration chamber .

Figure 4. Macrosonic-field mean SPL profile versus x-axis for cw excitation.

Figure 5. Schematic diagram of the sampling and measurement station.

Figure 6. Reductions of the particle emissions expressed in mass concentration and number concentration (for both ranges, micron and submicron particles) for the conditions studied. (a) is for 10 kHz and (b) for 20 kHz. The three bars refers to the applications of four transducers with 400 W each one (4T 400W), two transducers with 200 W (2T 200W) and four transducers with 80 W (4T 80W)

Figure 7. Evolution of the particles size distribution with the frecuency and power studied. The curves signalized OFF mean that the acoustic chamber was off and those signalized ON that the acoustic chamber was on. (a) is with 10 kHz and 4 transducers at 80 W, (b) is with 10 kHz and 4 transducers at 400 W, (c) is with 20 kHz and 4 transducers at 80 W, (d) is with 20 kHz and 4 transducers at 400 W.

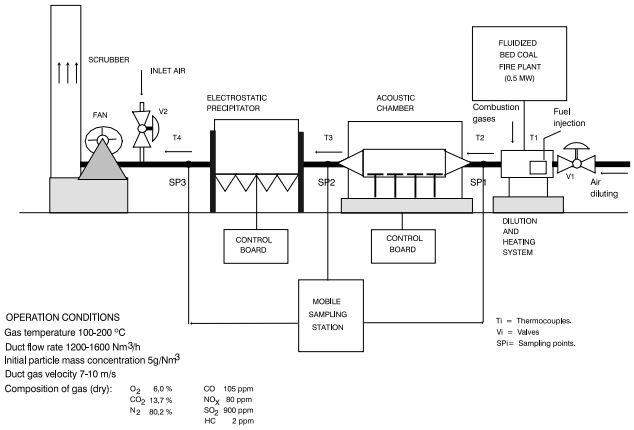


Figure 1.

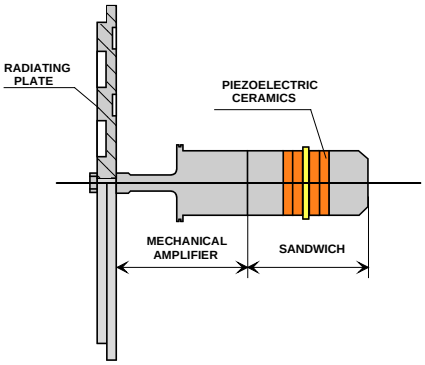


Figure 2.

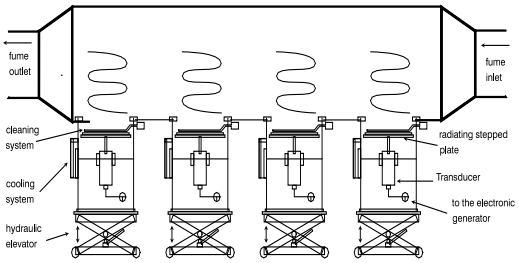


Figure 3.

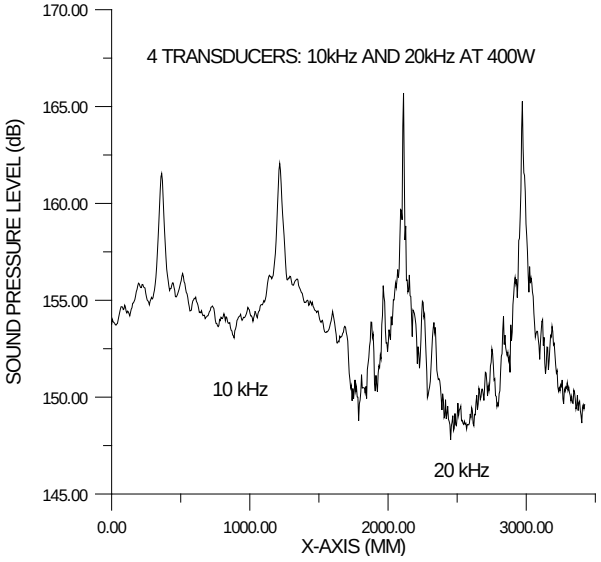
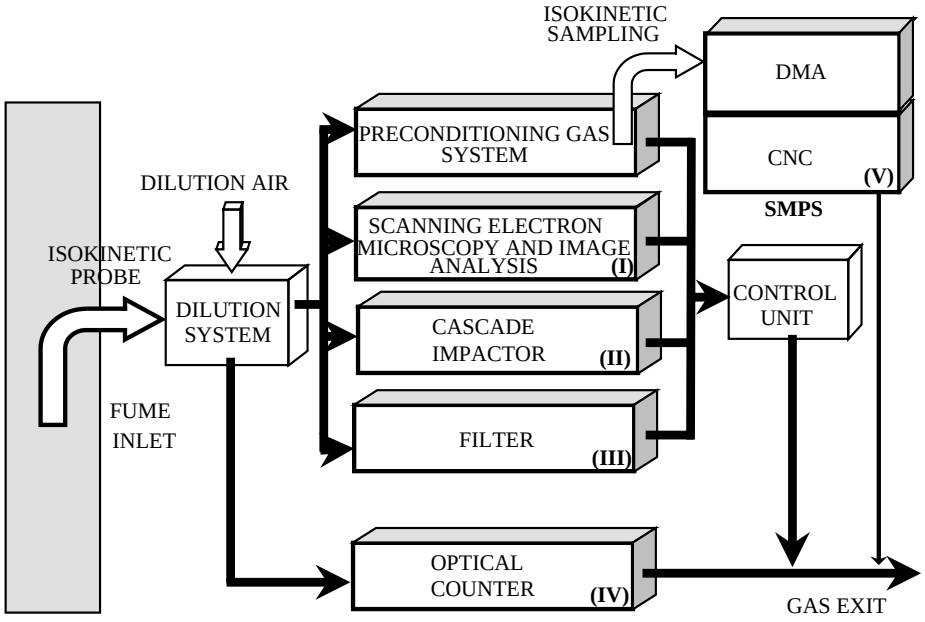
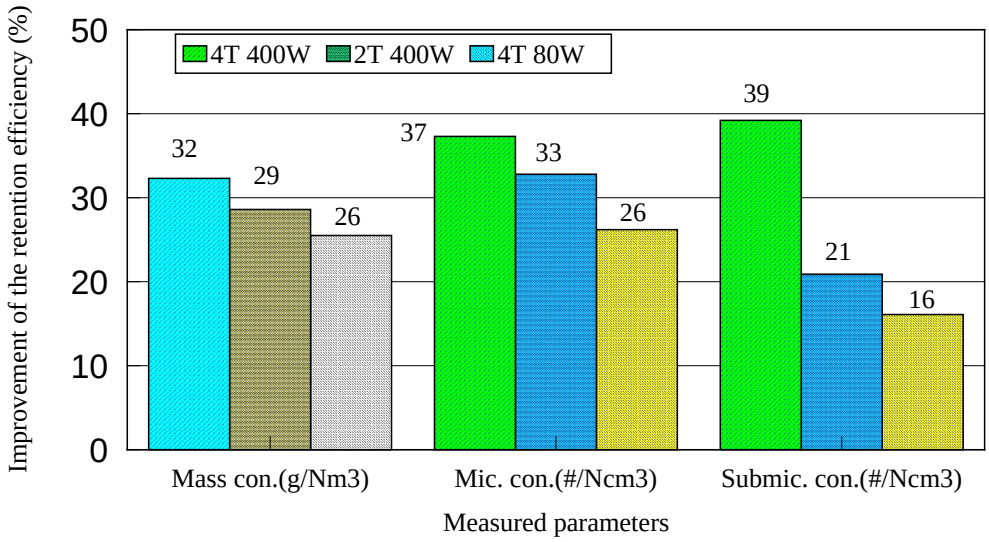


Figure 4.

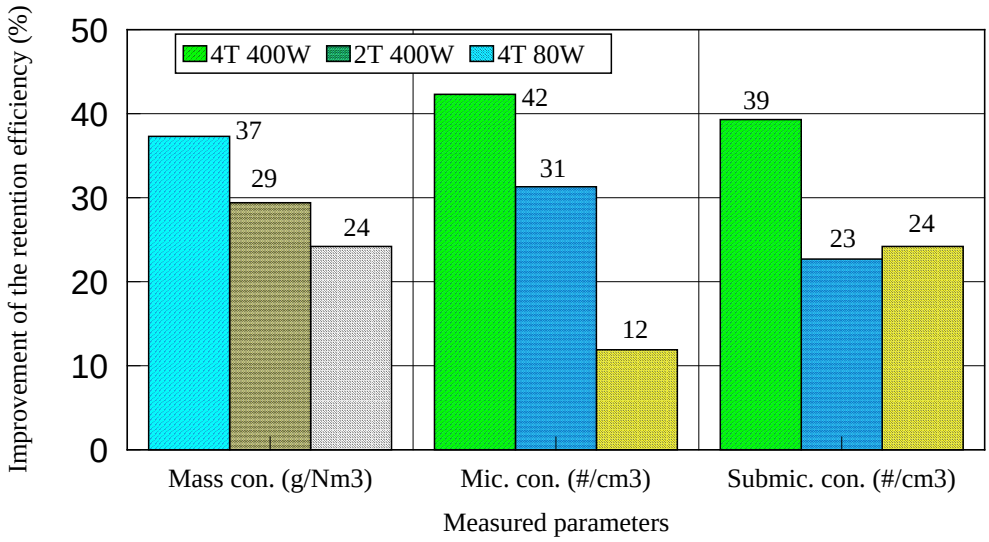


(I) Morphology and elemental composition
(II) Aerodynamic distribution and mass concentration.
(III) Mass concentration.
(IV) Size distribution and number concentration (0.7< Dp <10μm).
(V) Size distribution and number concentration(Dp <1μm).

Figure 5.


Improvement of the retention efficiency (%)
50
40
30
20
10
0
4T 400W
2T 400W
4T 80W
32
29
26
37
33
26
39
21
16
Mass con.(g/Nm3)
Mic. con.(#/Ncm3)
Submic. con.(#/Ncm3)
Measured parameters

(a)


Improvement of the retention efficiency (%)
50
40
30
20
10
0
4T 400W
2T 400W
4T 80W
37
29
24
42
31
12
39
23
24
Mass con. (g/Nm3)
Mic. con. (#/cm3)
Submic. con. (#/cm3)
Measured parameters

(b)

Figure 6.

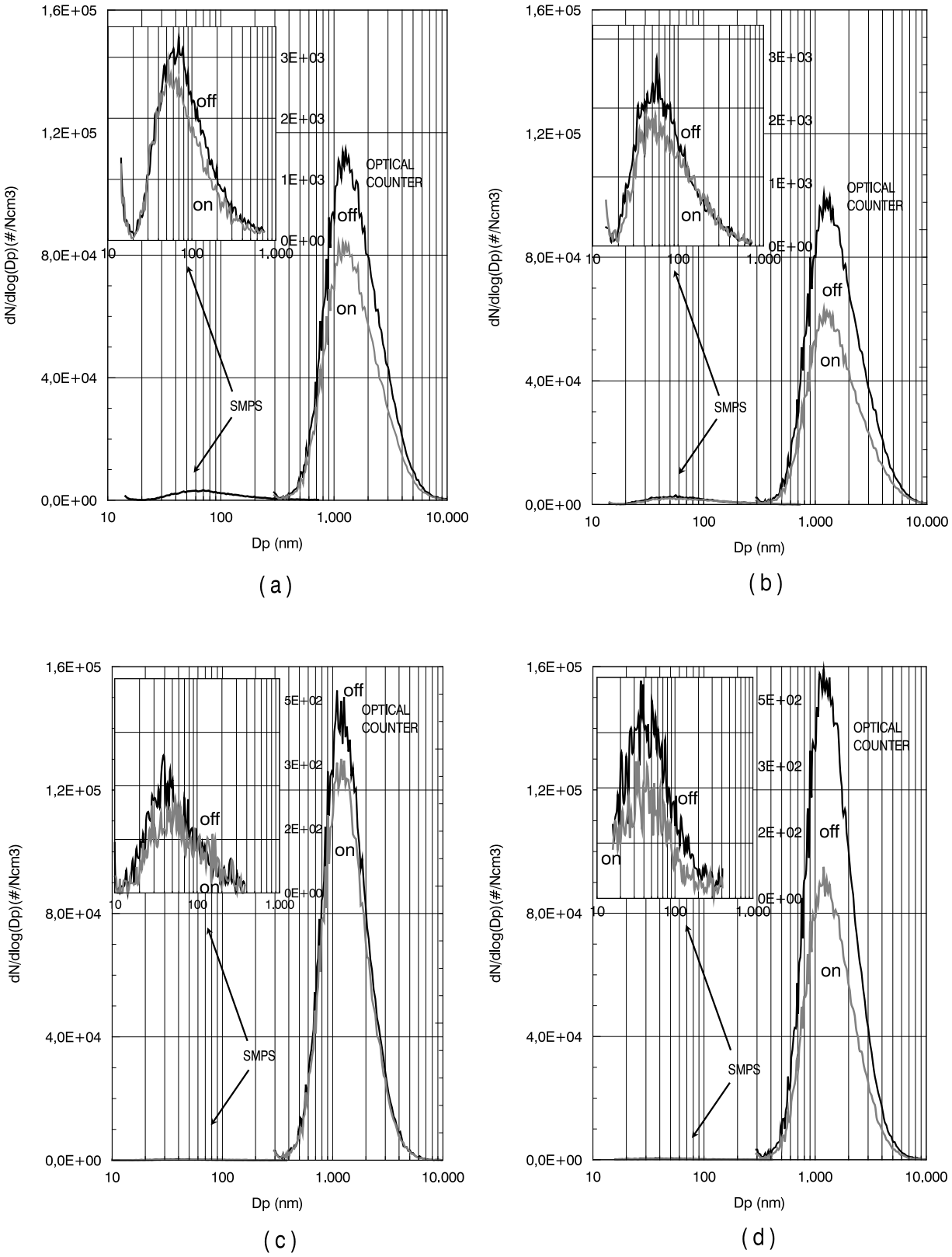

1,6E+05
1,2E+05
8,0E+04
4,0E+04
0,0E+00
dN/dlog(Dp)(#/Ncm3)
10
100
1.000
10.000
Dp (nm)
3E+03
2E+03
1E+03
0E+00
OPTICAL
COUNTER
off
on
SMPS
(a)
(b)
5E+02
3E+02
2E+02
(c)
(d)

Figure 7.