# REMOVAL OF PARTICLES AND ORGANIC COMPOUNDS ON MINIATURIZED IMPACTORS

F.P.Beraldo<sup>1</sup>; L.C.Santos<sup>2</sup>; E.W.Simões<sup>3</sup>; R.A.M Carvalho<sup>1,2</sup>; M.L.P.Silva<sup>2,3\*</sup> <sup>1</sup> Centro Universitário Sant'Anna, 02.011-000, São Paulo, SP, Brazil <sup>2</sup> Centro Estadual de Educação Tecnológica Paula Souza, 03.685-000, São Paulo, SP, Brazil <sup>3</sup> USP, Escola Politécnica, Laboratório de Sistemas Integráveis, 05.508900, São Paulo, SP, Brazil

Keywords: Impactors; Volatile organic compounds adsorption; Particle retention.

# ABSTRACT

The aim of this work was the simulation, production and characterization of miniaturized impactors for using in the removal of particles and organic compounds. The structures were simulated using FEMLAB 3.2B in order to understand the flow mechanisms. Miniaturized impactors (approximately 5 cm length, 2 cm wide and 500µm depth) were machined in acrylic using mechanical lathe and tested for the adsorption of volatile organic compounds and retention of particles in nitrogen flow or removal of viscous fluids in water flow. In nitrogen flow, adsorption of organic compounds is possible up to 380 mg of n-hexane. Moreover, 50µm and 13µm particles were easily retained at the inlet, with virtually 100% efficiency; however, 35nm particles can flow throughout the whole structure. In aqueous flow, viscous fluid, such as polydimethylsiloxane, 350 cST, showed retention even in dispersion 10% in weight whereas particles are not trapped. The simulated results showed good agreement with experimental measurements. These miniaturized impactors can be easily disassembled and are useful in sample pretreatment for chemical analysis, such as retention of small particles or microorganisms.

# 1. INTRODUCTION

Industrial and natural sources are constantly emitting particles to the atmosphere that are responsible, among others, for the formation of aerosols and smog. The particles size ranges from hundreds of angstroms to several microns in diameter and can cause several health and environmental problems. Therefore, air pollution is one of the major concerns for modern life and not only the removal but also the collection and analyses of air samples are quite important, especially to very small particles, i.e. aerosol, which can stay suspended on the atmosphere for a very long period [1-4]. Moreover, these particles can contain highly toxic materials, which [5] points out the importance of aside size and shape also determining the particle composition. Contaminants quite common in particles are heavy metals, which analysis presents several drawbacks. The analysis normally requires preconcentration, eventually by particle retention, due to the small concentration on the sample [6], however it is difficult collecting all these particles efficiently [7]. There are several other different air pollutants but special attention is given to organic compounds, volatile and semi-volatile, which might come from industrial sources and are an environmental issue [8,9].

The particles present on air are normally collected using gravitational effects if the particle diameter is up to 100 µm, by centrifugation for particles 10 µm large, and eventually 1 µm, with filter up to 0.1 µm large and electrostatic filters for smaller particles. The particle removal usually occurs on huge equipment for air cleaning reasons [10] and particle collection in smaller equipment for analytical purposes, such as: 1) particle selection and/or size determination, on analysis of indoor/outdoor air [11,12]; 2) calibration of particle size and concentration on artificially contaminated air [13]; 3) collection for further characterization in more complex analysis [14,15], etc. However, due to miniaturization, probably many of this smaller equipment will be changed to meso or microstructures soon. Even for analysis, miniaturization is a huge driving force, leading to lab-on-a-chip [16] and microTotal Analysis System, µTAS, conception [17]. Miniaturization also requires new approaches on equipment simulation and/or characterization [18,19].

For sample collection, as stated by Marple [20], impactors are of great importance because they are "simple devices, which relates the particle weight with the dimensional characteristics of the collector". Particles present in air are normally collected using impactors [21,22] and inside the most common impactor - the jet impactor - the flow is driven by a hole to hit a collector plate that traps the particles. The efficiency of this impactor can be increased just connecting several of these retention structures in order to selectively collect and/or trap the particles. In these structures the particles require a laminar flow, or at least not turbulent, to settle down in the collector plate. Another important parameter is the flow velocity once high velocity allows turbulence and back stream formation that can hinder the particle collection. Microorganisms can also be collected using the same apparatus, however it is customarily the use of wet processes instead a collector plate [23]. Some improvement might be achieved by the use of electrostatic barrier or ultraviolet [24] but these methods will also provide microorganism elimination [25].

Although impactors are simple and useful structures, their miniaturization was not fully attempted yet. Nascimento [26] miniaturized impactors, but only to adsorb volatile or-

<sup>\*</sup> malu@lsi.usp.br

ganic compounds (VOC's) from air and water. Therefore, the aim of this work was the simulation, production and characterization of miniaturized impactors for using in the removal in the removal of particles and organic compounds from gaseous or a liquid flow.

### 2. EXPERIMENTAL

The cascade impactor was chosen to miniaturization due to the high throughput and efficient retention for particles in a large size range [27]. The collection might use constrictions to enhance retention [28]. The impactor structure is similar to the one proposed by [26] and corresponds to a linearly scaling of May's cascade impactors [29] with two main differences: 1) the cells are aligned (symmetrically disposed) on the device, 2) the device is planar, i.e. uses only a slice of the original cylindrical design (500  $\mu$ m depth). The symmetric design of each cell is common nowadays and planar structures have many advantages on manufacturing, such as easiness on machining and sealing and lower secondary gravitational effects; furthermore it can be simulated using a 2D approach.

### 2.1 Manufacturing of the Impactors

The critical dimensions were optimized by simulation using FEMLAB 3.2b. Tests and simulation used fluid flow rates up to 10 standard mL/min for gaseous samples an up to 1 mL/min to liquid ones.

The structures are low cost devices composed by two pieces machined with a mechanical lathe and bonded with a 5  $\mu$ m thick adhesive tape (3M, YR-9767). Therefore, they can be easily disassembled and the inner content analyzed, for example by optical microscopy, in a similar way that occurs in the macroscopic structures. They were made in poly(methyl methacrylate), acrylic, in order to allow photographic and/or filming tests.

#### 2.2 Simulation

The flow behavior inside the structures was evaluated using incompressible Navier-Stokes 2D simulations on a FEMLAB 3.2b package (Pentium IV platform, 2.4 GHz, 2 GB of RAM). The chosen structure dimensions and mesh configuration used in FEMLAB program are showed in Figure 1.

The flow behavior was simulated using nitrogen or water for gaseous and liquid fluid, respectively. It was also simulated several different mixtures, which allows to determine the behavior of solutions, emulsions and dispersions.

The solutions were simulated using organic volatile compounds, acetone and 2-propanol, a serious environmental issue, moreover, silicone 350 cST was also used as high viscosity fluid carried by water. Sprays are emulsions, i.e. small particles, and might be approximately simulated supposing a 35 nm particle. Finally, dispersions were simulated with diameters of 50 $\mu$ m and 13 $\mu$ m, because, as stated in the introduction section, these dimensions correspond to particle sizes usually target on pollution control analysis.



Figure 1 – (A) Structures dimensions in mm and (B) Mesh Configuration.

The volatile compounds can be simulated considered only a two dimensional Newtonian viscous model. However, the model used for particle simulation is more complex and was formerly proposed by Heller [30]. The suspended particles were supposed to be spherical and can be modeled as very viscous liquid drops and the shape preservation can be taken introducing a hyper surface in this model, with the particle interface represented as the zero level set [30]. The particles path can be obtained by simulations as a function of the residence time of the particle inside the structure, which was arbitrarily adopted as 1 s for these calculations. This resident time is compatible with gaseous and liquid flows used on the experimental setup. The mean viscosity of the drops was 100 times larger than the viscosity of the fluid, and the mean density of the drops was equal to the density of the fluid. On these simulations, a small pulse of different size drops is injected in the structure; therefore the concentration of the drops is the same but not the size.

Furthermore, simulations to evaluate the optimal design regarding the critical dimensions, i.e. without constrictions issues that might lead to turbulences, were carried out. Figure 2 shows the design of the first cell of the impactor and the critical dimensions that were changed during the simulation. On these simulations the angle after the collector plate was varied from 45° to 30° and the distance between the cell entrance and the collector plate was varied in 60% from the original design (Figure 1). Moreover, the simulations used nitrogen as gaseous and acetone or water as liquid.

## 2.3 Characterization

The structures were characterized using Quartz Crystal Microbalance (QCM) to measure flow variations and optical microscopy to evaluate particle retention. Some structures were also filmed during injection of particles in order to evaluate flow mechanisms. The QCM equipment is home made and was designed specifically to characterize microstructures and particles interactions [31]. The system allows applying heating (300°C in 10 s) and tension (up to 5 V, DC) once these parameters are important for catalysis tests and microorganisms retention/elimination, respectively. The setup includes all plumbing system for liquid and gaseous analysis. Some measurements were carried out on a different setup from University of Puerto Rico-Humacao [32] just for comparison. Tests on gaseous and liquid flows were carried out using the injection of small pulses of particles or reactants, i.e. admission of a small and well-defined mass (~mg) or volume ( $\mu$ L) in a minimum period of time (<< 1s). Optical microscopy used conventional equipment (Baush&Lomb, model 311871) and filming (Sony, DSCW7 - P72, USA) as well.

The reactants are all P.A (Casa Americana SA, Brazil) but PDMS (polydimethylsiloxane, 350 cSt, Dow Corning Inc.) is industrial grade. Silicon oxide particles: 50 µm were obtained from Filite Inc., Brazil, 13 µm from Carborundum Abrasivos Ltda, Brazil and aqueous dispersion of 35 nm particles (Ludox-TM 50) from AdrichCo., USA. Spray of water and silicone were made by the injection of a small bubble (<0.01mL) on the gaseous or liquid fluid. For determining of liquid fluid behavior tracers and filming were used. Tracers are 10% wt. methylene blue aqueous solutions but in some solutions, 10% wt. of polyethylene oxide (PEO, 2,000,000 molecular weight, Aldrich Co., USA) was added for changing the viscosity. Whereas the methylene blue aqueous solution has the same viscosity of water, PEO aqueous solution is 10 times more viscous. This approach showed good performance on microstructures evaluation [33].

# 3. RESULTS

#### 3.1 Simulation

Two different types of simulation are described in this section: the optimization of impactor's dimensions and particle retention.

#### 3.1.1 Optimization of impactor's dimensions

Some dimensions of the structure are important to define the flow behavior: the collector plate and the angle after this plate, as illustrated in Figure 2. The flow was simulated in the structure from 0 to 10 standard mL/min for nitrogen and 0 to 1 mL/min to water, once they are the typical range for mesostructures. The chosen structure was considered the one that shows minimum turbulence and/or back stream and presents slow velocity in the neighborhood of the collector plate because this velocity defines the probability of retention.

As an example, Figures 3 A and B show the velocity profile for a 1 mL/min water flow with two different angles after the collector plate. In the Figure 3B the aspect ratio was maintained in relation to the optimized structure (Figure 3A) except for the angle and the corresponding velocity increasing due to this flow constriction occurs at the side of the collector plate, i.e. does not severely interfere with field velocity on the collector itself. Actually, it was observed for all simulated designs that the maximum and minimum velocities on the collector itself are almost the same without sudden variations along the plate. However, the small angle determines the velocity profile after the collector plate, i.e. on the next orifice, and possible turbulences due to constrictions, as also shown in Figure 3B.



Figure 2 – Design of the First Cell of the Impactor and critical dimensions: distance entrance/collector plate and angle after collector plate.



Figure 3 - Velocity profile using 1mL/min water as a fluid for two different structure dimensions, as stated in Figure 2 (A – normal design, and B – lower angle)

For all simulations, it was also observed that the main parameter influencing the velocity field in the neighborhood of the collector plate is the distance between the flow entrance and the collector plate. Whether the distance is quite small there would be some abrupt variations on the velocity near the plate and the velocity will approach zero only a small distance from this plate. On such conditions probably it will not be possible to retain the large particles due to the dragging provoked by the flow and Figures 4A to 4D show the streamline patterns for all variations described above. Nev(A) (B) (C) (D)

ertheless, these structures probably do not have important

turbulence, which may facilitate retention.

Figure 4 - Streamlines on the 1st cell using 1mL/min water as a fluid in the: (A) chosen structure, (B) structure with small distance between inlet and collector plate (C) structure with small angle after collector plate (D) structure with both variations (B+C)

Simulations with a viscous substance (silicone) injected in a water flow show a different behavior. In this condition the collector plate plays an important role and retention may occur in all structure. Figure 5 shows for one cell the several walls that must be considered during the simulation and Table 1 shows the boundary conditions assumed for these simulations and the obtained results. These conditions correspond to a very specific surface model on the software used: "no slip" means conditions with zero velocities on the walls, "slip" conditions indicated movable wall with no zero surface energy, and finally, "neutral" conditions are very similar to open walls, i.e. pressure near zero, with no zero surface energy.

On Table 1, the result "divergence" is probably due to the assumption that the silicone can interact with one or more lateral walls. On these conditions probably another phenomena, such as adsorption and capillary effects, would appear and would hinder the flowing of the fluid. All "no slip" condition (hypothesis 5) corresponds to a typical continuous

flowing and on such condition the obtained result shows the same velocity profile found with water or acetone, which seems unlikely due to the silicone high viscosity. Finally, the assumption that the collector plate interacts preferentially with the fluid allows obtaining convergence with much lower silicone velocity (100 time less) compared to water, which is coherent with experimental results.



Figure 5 - Walls of one cell of the impactor.

#### 3.1.2 Simulations of particle retention

Simulations of particle retention were also provided for gas and liquid fluids. In gas, the impactor retains efficiently particles of  $50\mu$ m in the first cell, particles of  $13\mu$ m travel throughout the first and second cell and 500 nm particles could not be retained at all. Figure 6 shows the particle concentration inside the structure after 0.1 s of the sample injection. A lighter area in the figure symbolized a more concentrated amount of particles. It is possible to notice a large amount of 500 nm particles leaving the structure but 13 µm particles or even 50 µm particle do not, which indicates easiness of retention.

Simulations of particle retention on liquid flow show that the impactor does not efficiently retain particles. Figure 7 shows the particle concentration inside the structure after 0.1 s of the sample injection. It is possible to notice a similar behavior for all particle size, with a high particle concentration at the outlet of the structure, especially for 13  $\mu$ m and 500 nm particles.

Hypothesis #	Software boundary conditions	Physical phenomena assumption	Obtained results
1	All "Slip"	Flow with no boundary layer definition	Divergence
2	Bottom/top "Slip" Others "No Slip"	Continuous flow but interaction with surface	Divergence
3	All "Neutral"	Any flow condition and/or surface interac- tion	Divergence
4	Bottom/top "Slip" Others "Neutral"	A two-dimensional flow is responsible for the flowing but there are some interaction with the walls	Divergence
5	All "No Slip"	Continuous flow	Convergence, but incoherent results
6	Collector plate "Neutral" Wall/bottom "No Slip" Top "Slip"	A three-dimensional flow is responsible for the flowing but the collector plate can inter- act with the fluid	Convergence and coherent results

Table 1 - Boundary conditions assumed during simulations and obtained results.



(A)
(B)
(C)
Figure 6 – Typical particles concentration for gaseous flow
(N2) after 0.1 s of sample injection. Lighter areas mean higher particle concentration. (A) 50 µm particles size (retention mainly in first cell); (B) 13 µm particles size (retention mainly in first and second cell) and (C) 500 nm particles size (no retention in the structure).



(A) (B) (C) Figure 7 – Typical particles concentration for liquid flow (water) 0.1 s after the sample injection. Lighter areas mean higher particle concentration. (A) 50 µm particles size (no retention in the structure); (B) 13 µm particles size (no retention in the structure) and (C) 500 nm particles size (no retention in the structure)

The differences on the interaction between the collector plate and particles due to fluid characteristics (gas or liquid) can be better understood in Figure 8. Figure 8 shows the 13µm particle concentration in the first cell for nitrogen and water fluids 0.05 s after the injection. As indicated in Figure 8A, a uniform and confined jet is formed due to the lack of interaction between the particle and the gas. However, in a liquid fluid (Figure 8B), the particles dispersion is not uniform because of the momentum change between the particle and the liquid. Also the high liquid density reduces significantly the mean free path of the particle and increases turbulence inside the structures. Therefore, as a more symmetric flow of particles probably will favor retention on the collector plate, gaseous fluid is more adequate to provide retention





### 3.2 Experimental Results

This item is divided in two sections: impactor behavior on gaseous and liquid fluids.

#### 3.2.1 Impactor behavior on gaseous fluid

Tests with gaseous fluid (nitrogen) were carried out using the injection of small pulses of particles, i.e. admission of a small and well-defined mass (~mg) in a minimum period of time (<< 1s). The impactor outlet was monitored by QCM analysis during particle injection. After each injection, optical microscopy was carried out to evaluate the positioning of particles retention. Also, after the test the structure was disassembled and the total amount of particles present on the structure was determined by weight.

QCM analysis does not show any signal when particles were injected showing that retention occurs to a large size range and with efficiency near or equal 100%. It was also possible to observe by optical microscopy a good agreement with simulations results once bigger particles (50  $\mu$ m and 13  $\mu$ m) were retained in the structure entrance, mainly 1st cell to 50  $\mu$ m particles and 1st and 2nd cell to 13  $\mu$ m. However, smaller particles (35 nm and spray drops) were spread out in the entire structure indicating that the retention mechanism does not rely on collector plate interaction.

Successive injections of 50 µm particles lead to the unsealing of the two-bonded side of the structure (rupture) but even though almost none particle can be seen outside the first cell by optical microscopy. Figure 9 shows two optical photographs of a detail of the collector plate on the 1st cell before (Figure 9A) and after (Figure 9B) the rupture. It is possible to notice that the region for flow passage is clogged by the particles trapped on the collector plate region and also in its lateral. These particles increase the flow impedance, allow the rupture and then, as can be seen in Figure 9B, some are spelled to the outside the structure.

Successive injections of 13  $\mu$ m particles allow the structure to be completely fulfilled in the 2nd cell and some particles even reach the 3rd one, however, the structure does not break easily. Figure 10 shows typical results obtained by optical microscopy on the collector plate of the 2nd (Figure 10A) and 3rd (Figure 10B) cell using 13  $\mu$ m particles.



Figure 9 - Two optical photographs of a detail of the collector plate on the 1st cell before (A) and after (B) the rupture of the structure using 50 µm particles



Figure 10 - Optical microscopy on the collector plate of the 2nd (A) and 3rd cell (B) using 13 µm particles

The retention efficiency was also evaluated by optical microcopy. The impactor outlet was directed to a plate wetted with a silicone film. The particle injection was carried out and the plate analyzed after each injection. It was not possible to observe any particle on the outlet after the particle injection or even in the outlet orifice of the 3rd cell. Figure 11 shows typical results for 13  $\mu$ m particles injection obtained on the plate in the outlet (Figure 11A) or on the orifice on the 3rd cell (Figure 11B) and, as can be noticed in the figure, no particle is seen.



Figure 11 - Optical microscopy of a plate located after the structure outlet (A) and the outlet orifice of the 3rd cell (B) using 13 µm particles.

Colloidal silica suspended in water (Ludox-TM50) was used to evaluate the nanoparticle behavior in the structure. The nanoparticles completely filled the structure but no rupture was found. Furthermore, optical microcopy does not show emulsion inside the structure but big particles. Due to the small size and high superficial area, spray and nanoparticles can easily coalesce. Moreover, the low velocity (high residence time) favors the contact between particles. Therefore, the mechanism changes in this situation because the interactions inside the flow became important whereas the collector plate does not play the same role. Similar behavior can be found using drops of water or silicone; however, due to the transparency of the drops, it is not easy to observe this phenomenon.

Vapor of organic compounds is not retained on the structure. Nevertheless, adsorption may occur if the structure is covered by an adsorbent film [26]. Figure 12 shows QCM analysis of the injection of a small amount of 2-propanol in a structure with (Figure 12A) or without (Figure 12B) adsorbent film. The use of adsorbent film allows retaining up to 380 mg of n-hexane but the same does not occur in the structure without film and even a single pulse (0.01 mg) can be detected.



Figure 12 - QCM analyses of structures with (A) or without (B) adsorbent film on the surface. Injection of (A) several pulses (1 to 6) of 84 mg vapor n-hexane and (B) two pulses (arrows) 0.01 mg of vapor 2-propanol.

Therefore, this structure can be used to retain a large size of particles and, with small modifications, also to remove volatile organic compounds [26]. Table 2 summarizes typical results obtained for injection from vapor of organic compounds to 50 µm particles in nitrogen fluid.

#### 3.2.2 Impactor behavior on liquid fluid

Although impactors are intended to particle retention in gas flow, miniaturization can increase secondary effects, such as capillary effects, and can favor retention in unusual conditions [33]. Therefore, tests using water as fluid were carried out using particles and silicone. Particles were not significantly retained and optical microscopy showed that these particles are spread out in all structure. Tracers were used to evaluate the flow mechanism inside the structure. Figure 13 shows a frame sequence of the injection of 0.01 mL of methylene blue aqueous solution in a water flow: the tracer hits the collector plate and spread out to the borders, on this condition probably the particles are swept away of the collector plate. Similar behavior can be found using more viscous solution, such as PEO emulsion.

On the other hand, if silicone is injected in small amount (0.01 mL) no change in baseline is detected at the outlet of the structure by QCM analysis, i.e. retention occurs. After four or more injections the flow decreases, eventually stops. The use of an adsorbent film (plasma polymerized hexamethyldisilazane thin film) covering the surface of the structure [35] increases the retention ability and after several injections the structure breaks off. Therefore, silicone was completely trapped inside the structure, probably in the collector plate, as observed in simulations. However, silicone might also be retained on the walls of the structure, due to their roughness, because silicone is a very viscous fluid. For a viscous fluid the interaction with a wall may easily lead to deformation and adhesion and the increase in retention us-

17

ing an adsorbent film seems to indicate that the adsorption occurs in all surfaces. Nascimento also shows the possibility of using impactors for VOC's adsorption on water [26].

Mixture	particle size	Maximum quantity retained		Efficiency of	Mada and a factor day
		(g/structure)	(mg/cm <sup>2</sup> structure)	retention (%)	Mechanism of retention
Particles	50 µm	0.03	5.4	~100	Trapped by the collector plate, mainly in the 1 <sup>st</sup> cell Correspond to the maximum possible packing of the silica particles
Particles	13 µm	0.06	11	~100	Trapped by the collector plate, mainly in the $1^{st}$ and $2^{nd}$ cell
Nanoparticles	35 nm	> 0.1	18	~100	Spread out on the whole structure. Coalescence observed
Spray (water and silicone drops)	From several angstroms to few micron			~100	Probably spread out on the whole struc- ture
n-hexane vapor		Not retained			Vapor removed if the surface is adsor- bent
Acetone vapor		Not retained			Vapor removed if the surface is adsor- bent
2-propanol vapor		Not retained			Vapor removed if the surface is adsor- bent

Table 2 - Typical results obtained with the injection from spray to 50 µm particles in nitrogen flow.



Figure 13 - A frame sequence of the injection of 0.01 mL of methylene blue aqueous solution in a water flow.

Therefore, miniaturized impactors showed some promising characteristics once they might be used for retention of particles on a large size range. Furthermore, these particles are previously separate according to their size on each cell and some improvement may be obtained for retention of VOC's if the impactor surface is covered by an adsorbent film. However, in liquid fluids its possible use is limited only for retention of viscous sample and should be enhance by the use of adsorbent films on the surface.

## 4. CONCLUSIONS

Impactors are structures normally used not only to remove particles from air but also to determine its size. In this work it was verified that miniaturized impactors could present the same function for a large size range of particles. Considering that this structure presents other two important applications, i.e. VOC's adsorption and removal of viscous substances from liquid flow, miniaturized impactors have a large variety of uses. Thus, the same structure might be used from VOC's removal to big particles collection without any further change, which is of prime importance on sample pretreatment for chemical analysis, especially on miniaturized structures, such as  $\mu$ TAS devices. Furthermore, this removal does not depend on gravitational or centrifugation effects, i. e. it is independent of mobile parts and/or motors.

The simulation of miniaturized impactors shows the importance of some dimensions of the structure: the collector plate and the angle after this plate. It also indicates the advantages of using such structures for particle retention in gaseous flow or viscous substances on liquid flow. Since the experimental results are in good agreement with simulation, several other not explored uses can be pointed out for these miniaturized impactors, such as microorganism collection.

#### **AKNOWLEDGEEMENTS**

Prof. M.M. Oka, University of S. Paulo and Faculty of Tecnology, S. Paulo, for useful suggestions. FAPESP, CAPES, CNPq and Advance it Programm, University of Puerto Rico, for financial support.

#### REFERENCES

- LIGHTY, J.S.; VERANTH, J.M.; SAROFIM, A.F., Journal of the Air & Waste Management Association 50 (2000) 1565-1618.
- KANAKIDOU, M.; TSIGARIDIS, K.; DENTENER, F.J.; CRUTZEN, P.J., Journal of Geophysical Research 105 (2000) 9243-9254.
- GROSJEAN, D., Atmospheric Environment 26A (1992) 953-963.
- DAMLE, A.S.; ENSOR, D.S.; RANADE, M.B., Aerosol Science and Technology 1 (1982) 119-133.
- 5. FOX, D.L., Analytical Chemistry 67 (1995) 183R-198R.
- HILL, S.J.; AROWOLO, T.A.; BUTLER, O.T.; COOK, J.M.; CRESSER, M.S.; MILES, D.L., Journal of Analytical Atomic Spectrometry 18 (2003) 170-202.
- CAVE, M.R.; BUTLER, O.; COOK, J.M.; CRESSER, M.S.; GARDEND, L.M.; MILESA, D.L., Journal of Analytical Atomic Spectrometry 15 (2000) 181-235.
- RATHBUN, R.E., Critical Reviews in Environmental Science and Technology 30 (2000) 129-295.
- 9. KOZIEL, J.A.; PAWLISZYN, J., Journal of Air & Waste Manage Association 51 (2001) 173-184.
- Residential Air Cleaning Devices: A Summary of Available Information, Office of Air and Radiation (OAR) Indoor Environments Division (IED) Washington, DC 20460 EPA 400/1-90-002, February 1990 (also available in: http://www.epa.gov/iaq/pubs/residair.html#Portable%20Units)
- SANTANA, J.D.A.M.; ARNOSTI, S.; COURY JR., J.R., Brazilian Journal of Chemical Engineering 18 (2001) 233-241.
- SUGIYAMA, T.; AMAGAI, T.I.; MATSUSHITA, H.; SOMA, M., Indoor Built Environment 8 (1999) 361-369.
- JAWOREK, A.; BALACHANDRAN, W.; LACKOWSKI, M.; KULON, J.; KRUPA, A., *Journal of Electrostatics* 64 (2006) 194-202.
- KAWANAKA, Y.; MATSUMOTO, E.; SAKAMOTO, K.; WANG, N.; YUN, S.-J., Atmospheric Environment 38 (2004) 2125-2132.
- LIU, C.Y.; MAO, X.L.; GONZÁLEZ, J.; RUSSO, R.E., Journal of Analytical Atomic Spectrometry 21 (2005) 778–784.
- KUTTER, J.P.; GESCHKE, O., Microsystem Engineering of Lab-on-a-Chip Devices, John Wiley & Sons, New York, 2004.

- 17. VILKNER, T.; JANASEK, D.; MANZ, A., Analytical Chemistry 76 (2004) 3373-3386.
- KANG, T.G.; KWON, T.H., Journal of Micromechanical Microengineering 14 (2004) 891–899.
- 19. XIA, H.M.; WAN, S.Y.M.; SHU, C.; CHEW, Y.T., *Lab on Chip* 5 (2005) 748–755.
- MARPLE, V., Aerosol Science & Technology 38 (2004) 247-292.
- LYNAM, M.M.; KEELER, G.J., Analytical and Bioanalytical Chemistry 374 (2002) 1009-1014.
- TELGHEDER, U.; KHVOSTIKOV, V.A., Journal of Analytical Atomic Spectrometry 12 (1997) 1-6.
- TERZIEVA, S.; DONNELLY, J.; ULEVICIUS, V.; GRINSHPUN, S.A.; WILLEKE, K.; STELMA, G.N.; BRENNER, K.P., Applied and Environmental Microbiology 62 (1996) 2264–2272.
- DOTTORI, M.; FAVA, G.M.; RUELLO, L., Indoor Built Environ 13 (2004) 309–314.
- XIAOHONG, Z.; KEJUN, L.; RUZHU, W.; LIPING, Z.; XU, L.X.; YAZHU, C.; XINQIAO, B.J.G.; JINGFENG, B.; HONGMIN, L.; XIAOJIANG, Y., *Chinese Science Bulletin* 49 (2004) 3306-310.
- NASCIMENTO A.P.; SILVA, M.L.P.; DEMARQUETTE, N.R.; CARVALHO, A.T., Materials Research 9 (2006) 1-9.
- DEMOKRITOU, P.; KAVOURAS, I.G.; FERGUSON, S.T.; KOUTRAKIS, P., Aerosol Science and Technology 36 (2002) 925-933.
- PEIRCE, J.J., Understanding Technology: New Concepts for Air Classification in Waste Processing & Resource Recovery, Proceedings of Twenty-First Annual Conference Engineering Education on a New World Order, San Diego, USA, 1991, pp. 325-328.
- 29. MAY, K., Journal of Aerosol Science 13 (1982) 37-47.
- 30. HELLER, M.; BRUUS, H., Physics Arquives, 05/18/2005 (available in Http://Arxiv.Org/Abs/Physics/0505126).
- SANTOS, L.C.; BERALDO, F.P.; HERNANDEZ, L.F.; CARVALHO, R.A.M.; SILVA, M.L.P., Revista Brasileira de Aplicações de Vácuo 25 (2006) 75-81.
- 32. SILVA, M.L.P.; FURLAN, R.; RAMOS, I., Development of Miniaturized Structures and Setups for Research and Teaching of New Concepts in Engineering, Proceedings of 9th International Conference on Engineering Education, San Juan, Puerto Rico, 2006, pp. 23-28.
- SANTOS, L.C.; BERALDO, F.P.; SIMÕES, E.W.; SILVA, M.L.P., Sensors & Actuators B – Chemical 130 (2008) 310-319.
- 34. SIMÕES, E.W.; SOUZA, S.G.; SILVA, M.L.P.; FURLAN, R.; PERES, H.M., Sensors & Actuators B – Chemical 115 (2006) 232-239.
- SILVA, M.L.P.; TAN, I.H.; GALEAZZO, E., Sensors & Actuators B – Chemical 91 (2003) 362-369.