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INDUSTRIAL DEPOLUTATION USING THE ULTRASONIC CAVITATION METHOD

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Abstract: *Ultrasonic cavitation represents a widely used process in the industry. Lately, it has been applied in modern and effective methods for industrial air pollution control. The phenomenon of ultrasonic cavitation, applicable in air pollution control in auto service facilities is based on the principle of fragmenting pollutant particles using the ultrasonic frequency produced by a set of ultrasonic transducers mounted on the bottom of a tank containing water. The particles, thus transformed into fine powder, settle at the bottom of the tank and are purged after a certain time. Polluted air from auto body shops is forced to pass through the water tank where the transducers vibrate. Afterward, the decontaminated air is expelled through the top of the ultrasonic tank and released into the atmosphere. The advantage of this method lies in the fact that polluted industrial spaces can be more easily decontaminated at lower costs compared to traditional pollution control methods based on the use of mechanical filters.*

Key words*: depollution, industrial emissions, heavy metals, Cd , Hg, Pb, NOx, SOx PM10.*

1. INTRODUCTION

The evolution of emissions can be associated with certain patterns. One of these indicates that pollutant emissions primarily associated with activities involving combustion processes (electric power producers, steel factories, cement factories) are generally decreasing and pertain to NOx, SOx, and PM10 emissions. This trend is in line with the improved environmental performance of these industries. Evidence suggests that EU policy is one of the key factors in these positive developments, as significant emission reductions (over 50% since 2010) have occurred in almost all countries that have joined the European Union. Similarly, greenhouse gas emissions, especially CO_2, are decreasing overall, although some countries exhibit a divergent situation. This article addresses aspects of industrial depollution in auto service facilities using a new method, ultrasonic cavitation. The experimental data presented in this article were obtained with the help of a specially designed installation for the depollution of particles and solvents in the auto body and paint shops. These experiments have been certified by a specialized firm in air pollution measurements.

2. ULTRASONIC CAVITATION

Since the main phenomenon used in the ultrasonic filtration process is ultrasonic cavitation, a phenomenon that occurs when ultrasonic waves propagate through a liquid medium, several research studies have been conducted on ultrasonic cavitation [1, 2]. Some of these studies, particularly those with applicability in the field of filtration, are presented below. These theoretical studies support the fact that the ultrasonic cavitation process is capable of producing chemical changes that support the air filtration capability through ultrasonic cavitation.

In multiple scientific studies, it has been observed that liquids exposed to ultrasound emit radiation and undergo chemical decompositions. The phenomena occurring during the sudden collapse of cavitation bubbles generated by the acoustic expansion of preexisting gas nuclei lead to the production of maximum temperatures ranging from 3000 to 50 000 K, depending on the ultrasonic system used. For example, chemical effects are compatible with temperatures in the lower part of the range, while discrete emissions from excited OH, C2 molecules, and CN molecules require temperatures above approximately 60 000 K.

The dynamics of cavitation bubble collapse are determined by the conservation of energy during the transformation of external energy into the kinetic energy of the liquid envelope, the heat content of gases, the enthalpy of chemical reactions, emitted radiation, and heat lost in the liquid. The explicit incorporation of changes in chemical enthalpy into the equation of bubble motion characterizes the complex and sometimes surprising effects associated with acoustic cavitation in liquids.

The theory related to cavitation bubble development shows that sonochemistry and sonoluminescence are interconnected and complementary manifestations of inexplicable imbalances in the rates and energies of chemical reactions.

Let R_0 și $R_{\max}$ be the equilibrium and maximum radii, respectively, of a spherical gas bubble subjected to an ultrasonic field of frequency f (in kHz) and pressure P_a (in atm, 1 atm = 10^5 Pa). These wave parameters will be noted as (f, P_a). The pressure magnitude is related to

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the acoustic intensity I_a, through the equation:

$$P_a = 2(2\rho C_L I_a)^{1/2},$$

where ρ is the density of the liquid medium and C_L – sound speed.

The initial pressure inside the cavitation bubble is given by the equation:

$$P_{g,e} = P_0 - P_{vap} + \sigma / R_0,$$

where P_0 is the hydrostatic pressure; P_{vap} = 3.0 kPa – vapor pressure in the liquid; σ = 0.072 N/m – surface pressure at a temperature of 300 K.

As long as the gas pressure during isothermal expansion decreases by a factor $z = (R_{\max} / R_0)^3$ while regarding P_{vap} it is assumed that the chemical composition of the gas remains constant when the cavitation bubble hits $R_{\max}$ is a z function.

Starting from $R = R_{\max}$, $dR / dt = R^{'}(0)$ the cavitation bubble contracts under the external pressure:

$$P_{\text{ext}} = P_0 + \varphi P_a,$$

where $\varphi P_a = \int_{-t\,exp}^{t} \sin(2\pi f t')d\left(t'/_t\right)$ is the acoustic pressure at time t. As long as 25 μs, which represents half a period at the frequency of 20 kHz of the ultrasonic wave, is a much longer time than the implosion time of the cavitation bubble, which is only a few μs it can be assumed that P_{ext} can be considered constant. This approximation works well even at higher frequencies because the bubble implosion times are proportionally smaller. Therefore, the mechanical work done by the liquid in the contraction of a cavitation bubble of radius R is given by the equation:

$$W_{ext} = 4\pi P_{ext}(R_{max}^3 - R^3)/3 + 4\pi\sigma(R_{max}^2 - R^2).$$

The outer mechanical work $Wext$, from which any heat is subtracted H_d dissipated in the liquid during the implosion of the bubble, must be converted into the kinetic energy of convection of the liquid shell of the bubble KE_{liq}, plus mechanical compression Wg performed by the gas bubble:

$$W_{ext} - H_d = KE_{liq} + W_g = 2\pi R^3 \rho R'^2 + W_g,$$

where $KE_{liq} = 2\pi R3\rho R'^2$ for an incompressible liquid. The power transmitted to the gas is given by the equation:

$$\frac{dW_g}{dt} = -\frac{P_g dV}{dt} = -[\delta k_B T/(1 - b\delta)]4\pi R^2 R', (R' < 0),$$

where P_g is the instantaneous total pressure of the gas inside and in the immediate vicinity of the bubble, δ is the density of the gas, k_B is Boltzmann's constant, T is the temperature of the environment and $b = 3.05\ E - 2M - 1$ is the Van der Waals constant of water. This mechanical action results in heating the gas and changing its chemical composition.

$$W_g = H_g + Q.$$

The heat $H_g = n\langle \text{Cv}\rangle(T - T_{amb})$ and the chemical energy $Q = \sum\langle \Delta H_{Fi}\rangle\,(n_i - n_{i0})$ can be evaluated from the instantaneous chemical composition of the mixture and its and from the temperature n which represents the number of molecules $n = \sum n_i, n_{i0} = n_i(0)$.

The relation $\langle \text{Cv}\rangle = k_B / (\gamma - 1)$ is the average molecular heat capacity of the mixture, $\gamma = C_p / C_v$ and $\langle \Delta H_{Fi}\rangle$ is the heat required to form a bubble in J/molecule. The values $\langle \Delta H_{Fi}\rangle$ and $\langle\gamma\rangle$ are calculated for the temperature of 2000 K. For example, for $P_{g,e}$ = 1 atm and $R_{max} / R = 10$, z = 1xE3 at a temperature of 298 K, the polytropic index

$$\gamma = \frac{(1.67 \cdot 1 \cdot 10^{-3} + 1.33 \cdot 3 \cdot 10^{-2})}{3.1} \cdot 10^{-2} = 1.34$$

is considerably smaller than γ = 1.66.

Losses of water vapor from the bubble during the early phase of implosion can slightly increase its values γ compared to those calculated at $R_{\max}$. Thus the equation T_{amb} = 300 K becomes:

$$T = 300 + (W_g - Q)(\gamma - 1)/nk_B,$$

$$OH \Leftrightarrow O + H.$$

At equilibrium, all possible reactions between O- and H- containing two atoms can occur (O_2, H_2), of three atoms (HO_2, O_3) and four atoms (H_2O_2) X_i as presented below:

$$H_2O + M \leftrightarrow H + OH + M,$$
$$OH + M \leftrightarrow O + H + M,$$
$$H_2O + H \leftrightarrow OH + H_2,$$
$$2OH \leftrightarrow O + H_2O,$$
$$O + OH \leftrightarrow O_2 + H,$$
$$2O + M \leftrightarrow O_2 + M,$$
$$2OH + M \leftrightarrow H_2O_2 + M,$$
$$H + O_2 + M \leftrightarrow HO_2 + M,$$
$$2HO_2 \leftrightarrow H_2O_2 + O_2,$$
$$2H + M \leftrightarrow H_2 + M,$$
$$O + H_2 \leftrightarrow OH + H,$$
$$HO_2 + O \leftrightarrow OH + O_2.$$

3. PHASES OF THE APPEARANCE OF THE CAVITATION BUBBLE IMPLOSION

The four phases, filmed, of the appearance and implosion of a cavitation bubble are shown in Fig. 1.

The formation of the cavitation bubble takes place as a result of a stretch-compression process with ultrasonic level frequencies, as can be seen in Fig. 2.

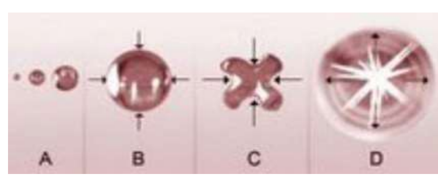

Fig 1. Formation and implosion of a cavitation bubble: *a* – the formation of the cavitation bubble; *b* – expansion of the bubble; *c*, *d* – implosion of the cavity bubble.

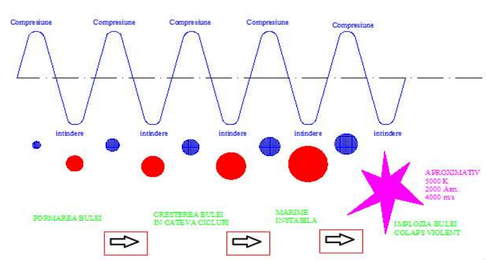

Fig. 2. The stretching-compression process with ultrasonic frequency that leads to the formation of the cavitation bubble.

Ultrasounds propagating through liquid media, through the phenomenon of ultrasonic cavitation, produce multiple effects known in specialized literature [3, 4 and 5]:

- ultrasonic homogenization through which the very intense field of vibrations and shearing forces allow the mixing and reduction of the particle size, resulting in uniformly mixed suspensions. Therefore, sonication is used to produce homogeneous colloidal suspension with narrow distribution curves.
- dispersion of nanoparticles, deagglomeration and wet grinding of nanoparticles are possible by producing low-frequency ultrasounds that break down agglomerates and reduce particle size. Shear forces during cavitation, in particular, produce jets of liquid that accelerate the particles in the liquid, which collide with each other (particle collision), so that they break and erode accordingly. This results in a uniform and stable particle distribution, preventing sedimentation. The phenomenon is extremely important in various fields, including nanotechnology, materials science, and pharmaceuticals.
- Emulsification and the mixing of liquids represent another application of ultrasound transmission in liquids. Ultrasonic probe systems are employed to create emulsions and mix liquids. Ultrasonic energy induces cavitation, the formation and sudden collapse of microscopic bubbles, generating intense local shear forces. This process aids in emulsifying immiscible liquids, resulting in stable and finely dispersed emulsions.
- Mass extraction occurs due to cavitational shear forces, leading to the disruption of cellular structures and an increased mass transfer between solid and liquid. Ultrasonic extraction is widely used to release intracellular material, such as bioactive compounds, for the production of high-quality botanical extracts.
- Degassing and deaeration are employed to remove gas bubbles or dissolved gases from liquids. The application of ultrasound causes gas bubbles to rise and float to the top of the liquid. Ultrasonic cavitation makes degassing a quick and effective procedure. It is crucial in various industries, including painting, hydraulic fluid production, or food and beverage processing, where the presence of gases can adversely affect the quality and stability of the product.
- Sonocatalysis is a process that combines acoustic cavitation with catalysts to enhance chemical reactions. Cavitation generated by ultrasonic waves improves mass transfer, increases reaction rates, and promotes the production of free radicals, leading to more efficient and selective chemical transformations. Probe transducers are commonly used in laboratories for sample preparation. They are utilized to homogenize, disaggregate, and extract biological samples such as cells, tissues, and viruses. The ultrasonic energy generated by the probe disrupts cell membranes, releasing cell contents and facilitating further analysis.
- Disintegration and destruction of cells ultrasonic cavitation is used to disintegrate and break down cells and tissues for various purposes, such as extracting intracellular components, microbial inactivation, or preparing samples for analysis. High-intensity ultrasonic waves and the resulting cavitation generate mechanical stresses and shear forces, leading to the disintegration of cellular structures. In biological research and medical diagnosis, ultrasonic cavitation is employed for cell lysis, the process of breaking open cells to release their intracellular components.

The ultrasound energy disrupts cell walls, membranes, and organelles, allowing the extraction of proteins, DNA, RNA, and other cellular constituents.

Ultrasonically induced cavitation forms the basis for numerous technological applications, ranging from domestic activities to medicine and extending to military or space applications. The cavitation phenomenon involves the formation, growth, and implosion of bubbles or cavities containing vapors, gases, or air within the volume of a liquid.

Cavitation can be divided into 3 categories: gas medium, vapor medium, pseudocavitation.

Vapor-based cavitation is characterized by the rapid transformation of the liquid in which the phenomenon occurs into vapor when the pressure drops below the vaporization pressure, specifically when pm < pv. The bubble explosively expands, leading to an extreme vaporization process within the liquid volume.

Gas cavitation is based on the transfer of gas from the liquid where the process takes place into the cavitation bubble, followed by an increase in the bubble's volume. The mechanical pressure at which this mass transfer occurs at the interface of the cavitation bubble can be either lower or higher than the vaporization pressure ($pm \geq$ pv).

Pseudocavitation involves the enlargement of the cavitation bubble due to the initial gas expansion, followed by a decrease in pressure without the addition of gas or vapors. Typically, in engineering applications, vapor cavitation is encountered due to its destructive effects on solid materials, the generation of noise and vibrations, or changes in the hydrodynamic field.

The cavitation process itself is inherently unstable and variable. Taking this into account, several types of cavitation are distinguished: fixed cavitation, traveling cavitation, swirling cavitation and vibratory cavitation.

Fixed cavitation occurs when the current no longer has contact with the solid body, resulting in a cavity fixed to the wall, with a larger diameter than the cavitational bubble. In the area adjacent to the liquid, numerous traveling cavitation bubbles can be found. They increase in size upstream of the fixed cavity, remain the same shape in the transient zone, and then implode downstream. Traveling cavitation presents 3 geometric shapes that are found with predilection: traveling bubbles, traveling spots and annular traveling bubbles. In the cavitation of the traveling bubbles, the appearance of some spherical geometric shape cavitation bubbles that grow very quickly in size, while they are transported along the part to finally collapse suddenly in the low pressure area.

The cavitation of the spot or traveling band type is characterized by the flattened shape that can be completely or partially wrapped around the piece around which it is formed. The two types of cavitation can appear randomly in areas with lower pressures. Cavitation in the category of ring-shaped traveling bubbles can only appear on the surface of axially symmetrical parts.

This name comes from the annular arrangement of macroscopic bubbles, with an irregular shape, around the part immersed in the liquid. These rings form and collapse rapidly within a small area. Research shows that the tension σi increases slowly with speed in the case of cavitation of annular traveling bubbles and is not dependent on the air content $\alpha > 4$ppm (ppm = parts per million).

Vortex cavitation occurs in the central area of the vortices where a high velocity and a low pressure occur, being able to reach the vaporization pressure.

4. MATHEMATICAL MODELING OF THE ULTRASONIC SYSTEM

Mathematical modeling using the finite element method is currently a working method that can be found in many scientific fields, including medicine. Engineering has benefited from the contribution of this method for about 40 years, being used mainly due to its results that approach the real behavior of the systems with a precision of about 90% [6, 7].

In order to obtain results as close as possible to reality, entering the input data is extremely important. In this sense, the steps taken to solve the proposed problem will be presented below. This problem consists in determining the vibration modes and optimal vibration frequencies, useful in obtaining the cavitation phenomenon.

In the first stage, the defining one, the type of discretization element used in solving the proposed problem is chosen. In the studied case, two discretization elements are used, since the analysis is of the modal type and the vibration modes come from the piezoceramic elements. The phenomenon of piezoelectricity is analyzed and studied by using an element, for example, of the SOLID98 type (ANSYS software). It transforms electrical energy into mechanical energy being a Coupled Field type element.

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To create the proposed model, four types of material are used as follows:

- steel – for modeling the lower part of the tub;
- aluminum – for modeling the reflector and the concentrator of the ultrasonic system;
- piezoceramic material – for piezoceramic disks;
- the silicone adhesive for modeling the adhesive layer with which the transducer is fixed to the bottom of the tub.

5. THE GEOMETRIC MODEL OF THE ULTRASONIC SYSTEM

Understanding how the ultrasonic system works is extremely important for obtaining results close to reality [8, 9 and 10]. In this sense, the two piezochemical disks are put under voltage as follows: on their common surface, the voltage U = 200 V will be applied, and on the other two surfaces in contact with the reflector and, with the amplifier, the voltage U = 0 V will be applied .

Since the vibratory system can only work if there is an area with minimum vibration amplitude or embedment at its level, the representation of the lower part of the tub as a disk with a radius equal to half of the distance between two adjacent transducers was considered in the analysis. At this distance, the oscillations produced by two transducers positioned next to each other become very small, almost zero. Otherwise, the oscillations can overlap and give rise to unwanted, uncontrollable vibrations. Taking into account all these, an embedment area located on the periphery of the disc, which represents the lower part of the tube, was considered.

The piezoceramic transducer used to obtain the ultrasonic cavity phenomenon togeteh with its componets are presented in Fig. 3.

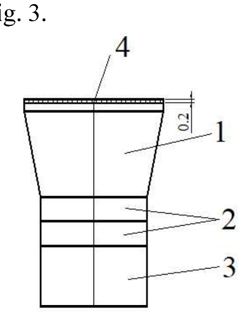

Fig. 3. Piezoceramic (1 – ultrasonic amplifier; 2 – piezoceramic elements; 3 – ultrasonic reflector; 4 – adhesive layer).

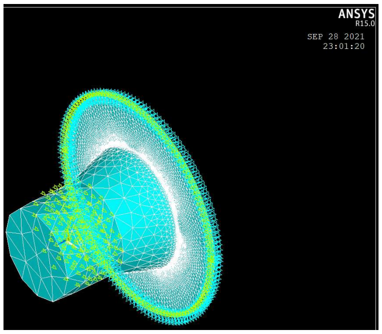

Fig. 4. Presentation of the input data required for the simulation of the ultrasonic cavitation process.

6. EXPERIMENTAL STAND USED IN THE RESEARCH

The figures below show an overview of the filtration system based on the phenomenon of ultrasonic cavitation.

The filtering system based on the acoustic cavity created in this way was installed in the paint shop of a specialized service. Figure 5 shows the images during the installation and of the air quality measurements. As can be seen in Fig. 5,*a* , the filter installation is shown, which is connected through the piping on the left side to the areas where, in the work station, grinding, a high level of pollution occurs. The vertical piping is connected to the fan that extracts the filtered air which is then sent outside the tin-painting workshop. In Fig. 5,*b*, the air intake piping placed in the filtration area is shown.

It can be seen in Fig. 6 how the experimental stand was placed in the tinning section of a service where the air pollution measurements are to be made.

a b

Fig. 5. Realization of the filter system assembly that uses the ultrasonic cavitation: *a* – frontal view; *b* – side view.

Fig. 6. Location of the filtration system.

7. EQUIPMENT USED FOR MEASUREMENTS

The following measuring devices and systems were used to perform the measurements that demonstrate the effectiveness of air filtration through this new method:

a) ISOSTACK BASIC TCR TECORA isokinetic sampling pump

To carry out the measurements, the measurement scheme presented by the manufacturer in Fig. 7 was used. As can be seen, before the sampling probe there is a condensing unit attached to the isokinetic sampling pump connected to the measurement sensors located in the pump. A detail of the front panel of the pump is shown at the top of the diagram.

b) SICK MAIHAK model 3006 automatic gas analyzer with standard gas cylinder

The measuring principle of the FID3006 instrument uses a flame ionization detector to convert the concentration of hydrocarbons in a sample into an electrical signal. This is done using a hydrogen flame and hydrocarbon-free air in a burner around which an electric field is placed. The hydrocarbons in the sample are cracked to form CH fragments that are oxidized to CHO+ ions. The ion flux is measurable and proportional to the carbon content of organic substances.

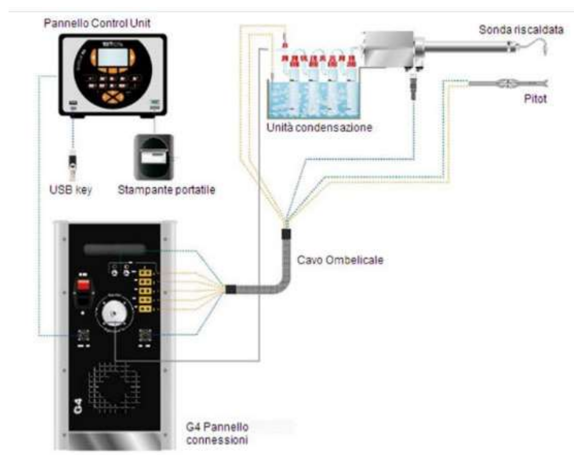

Fig.7. Measurement scheme using the SICK MAIHAK model 3006 device.

Fig. 8. Gas analyzer SICK MAIHAK model 3006.

Fig. 9. Testo 350 – analysis unit for flue gas and emissions analyzer.

c) Testo 350 portable flue gas analyser

Testo 350 is a portable flue gas analysis device with a very high degree of accuracy. Its structure is based on a control unit and an analysis unit.

8. RESULTS OF PHYSICAL-CHEMICAL EXPERIMENTAL TESTS

The measurements were made for three power percentages of the pump (50%, 75% and 100%), which forces the air and emissions in the tank were the filtration by cavitation occurs. After the filtering system there is a ventilator that extracts the air between the liquid and cover sending it into the atmosphere. The air is tested for different working powers of the ventilator (50%, 77% and 100%).

Table 1 shows the physical parameters of the residual gaseous effluent and the geometric parameters of the point emission source.

It can thus be said that the air filtration system based on the production of the ultrasonic cavitation phenomenon more than fulfills the functional role for which it was designed, the results obtained being below the values imposed by the national or European regulations, sometimes even far below their limit. According to Romanian Law 462/1993, the permissible limit values are as follows: VOC – 100 mg/Nm3; NOx – 350 mg; powders – 88 mg/l.

9. CONCLUSIONS

The mathematical modelling of the processes and phenomena that take place in the ultrasonic system that leads to the realization of the phenomenon of ultrasonic cavitation is a very important stage in the design of this system. Since the processes take place at very high frequencies and the vibration amplitude is very small, it is very difficult, almost impossible to observe or study the phenomena in this system. It is the mathematical modelling based on the finite element method that can provide the prediction of the behaviour of the ultrasonic system. Two models that prove to be useful in the physical realization of the ultrasonic system and in its operation were realized.

In the first CAD-FEM model presented, we predicted the behavior of the ultrasonic system at several modes of vibration. The most useful work frequency was found to be f = 35596 Hz.

In the second mathematical model, it was determined the principles underlying the practical determination of the thickness of the silicone adhesive layer required to attach the transducer to the bottom of the tank. This is a very important technological parameter that must fulfil two very important requirements necessary for the operation of the ultrasonic system:

- fixing on the bottom of the tub;
- the optimal transmission of ultrasonic vibrations from the ultrasonic transducer in the lower part of the tank where the phenomenon of ultrasonic cavitation occurs.

Following the experiments carried out in the auto tinning workshop, the following were concluded:

The limit values of the physical parameters of the residual gaseous effluent are below the limit imposed by the legislation in force, which proves that the depollution equipment presented is effective and can be implemented in all situations where it is desired to obtain an advantageous quality/price ratio.

Table 1

Physical parameters of the residual gaseous

Source	Pollutant	Concentration (mg/Nm3)				VLE [mg/Nm3]	Mass flow
		After filter, 50%	After filter, 75%	After filter, 100%	Average		
Before filter, 50% of power	Powders	0.48	0.44	0.42	0.44	50	0.06
	VOC/TOC*	20	18	20	19.33	50	1.78
	NOx	0.1687	0.1831	0.1485	0.1667	250	0.012
Before filter, 75% of power	Powders	0.46	0.42	0.41	0.43	50	0.06
	VOC/TOC*	22	19	18	19.66	50	2.87
	NOx	< 0.1364	< 0.1365	< 0.1312	< 0.1347	250	< 0.018
Before filter, 100% of power	Powders	0.55	0.54	0.47	0.52	50	0.05
	VOC/TOC*	26	26	24	25.33	50	4.2
	NOx	< 0.1363	< 0.1369	< 0.1362	< 0.1364	250	< 0.022

VOC – Volatile Organic Compounds;
TOC – Total Organic Carbon;
NOx – Nitrogen oxides;
* – Calculated volumetric flows.

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