Air Quality, Atmosphere & Health (2019) 12:305–310
https://doi.org/10.1007/s11869-018-00656-7

Decontamination of Diesel particles from air by using the Counterfog® system

J. L. Pérez-Díaz[1] · F. J. Llerena-Aguilar[1] · T. Martín-Pérez[1] · J. Sánchez-García-Casarrubios[2] · E. Ruiz-Navas[3]

Received: 18 October 2018 / Accepted: 28 November 2018 / Published online: 13 December 2018

Abstract
The existence of particles with diameter under 10 μm in air is strongly correlated with respiratory diseases. These particles are profusely produced by heating systems, traffic, and Diesel engines creating a serious problem to modern cities. Natural mechanisms removing particles from the atmosphere are too slow to deal with the huge amount of particles daily released by human activity. The objective of this work is to measure the effectiveness of a new technology called Counterfog® to eliminate airborne particles. The results show that Counterfog® is able to wash out PM10, PM5, and PM2.5 Diesel-generated airborne particles quite efficiently.

Keywords Diesel exhaust particles · PM2.5 · PM10 · Counterfog

Introduction

There is a serious health risk associated with exposure to micron-sized solid particles in suspension (Dockery et al. 1993; Pope et al. 1995; WHO 2013). Direct exposure includes direct inhalation from air or ingestion of those deposited on food (EEA 2017). It is generally admitted that particles with a diameter lower than 10 μm (known as PM10) can penetrate the respiratory system, reaching high respiratory tract and bronchi while those under 2.5 μm can reach bronchioles and alveoli (Nel 2005).

The presence of solid particles floating in air is especially severe. It has been demonstrated that exhaust and non-exhaust traffic-related particles contribute almost equally to this problem (Grigoratos and Martini 2014). Non-exhaust traffic particles are originated by brakes, clutches, tires, roads, and resuspended material. Exhaust particles are usually associated with the combustion process of Diesel engines and heating systems (Fenger and Tjell 2009; Lucking et al. 2011).

Natural mechanisms removing particles from the atmosphere are known to be dry deposition or fallout and scavenging. The first one is produced by gravity driving solid particles down, while in the second phenomenon particles act as condensation nuclei to create water raindrops that eventually fall. These raindrops may supposedly wash out other particles and droplets as they fall (Allaby 2003). However, it is well-known that raindrops are not very effective removing micron-sized particles which can remain floating in air for days (Greenfield 1956). Thermal inversion in the atmosphere hinders the scattering of pollutant particles from urban areas to others as well (EEA 2012).

Recently, a new technology based on the interaction of fogs with the polluted air—called Counterfog®—has been proposed to reduce the concentration of air pollutants in large areas (Martín-Pérez et al. 2018; Pérez-Díaz et al. 2018; Casarrubios et al. 2018). Using just water and compressed air Counterfog® creates a conic jet of fog composed of micron-sized droplets that are claimed to wash out particles from the surrounding air (Pérez-Díaz application EP 17382293). Such effectiveness is based on the use of droplets of the size similar to those particles to remove by aggregation with the water droplets. Counterfog® uses just water and air maximizing environmental friendship. In the present work, the effectiveness of such a system to remove exhaust particles from air is tested in laboratory.

✉ F. J. Llerena-Aguilar
francisco.llerena@edu.uah.es

1 Departamento de Teoría de la Señal y Comunicaciones, Escuela Politécnica Superior, Universidad de Alcalá, 28805 Alcalá de Henares, Madrid, Spain

2 San Jorge Tecnológicas S.L., 28341 Valdemoro, Madrid, Spain

3 Instituto Pedro Juan de Lastanosa, Universidad Carlos III de Madrid, Avda. Universidad 30, 28911 Leganés, Madrid, Spain

Methods

Fog dynamics laboratory

Tests were carried out in the Fog Dynamics Laboratory created in the EU-funded Counterfog® project. This laboratory was designed to create different kind of fogs using the Counterfog® system (Fig. 1). The laboratory has two test rooms that can be isolated from the outside climatic conditions. The test room dimensions are 2.46 m × 3.10 m × 2.13 m and it is provided with equipment that allows the temperature and humidity control.

The Counterfog® system consists in a nozzle which creates a cleaning fog. This fog can be of just water or contain a neutralizing compound. For these experiments, only fogs made of water were used. The droplets size of the fog can be changed depending on the water and air pressures that can be adjusted at will.

Air contamination method

Before the air contamination, the laboratory's temperature was set 25 °C in order to be constant during the test to ensure that these factors will not affect the generation of the fog. Then, gases and solid particles generated in a four-stroke Diesel engine of Euro 1 kind are conducted to the room (Fig. 2). The number and size of the particles was monitored by a particle counter (8306 Handheld Particle Counter, Particles Plus, Massachusetts, USA). Number of particles per liter are measured between 0.3 and 10 μm.

Before proceeding to the decontamination of the air, few minutes are required to ensure the homogeneity of the air in the laboratory. A natural deposition rate due to gravity and described by Stokes viscosity law is therefore determined with those data.

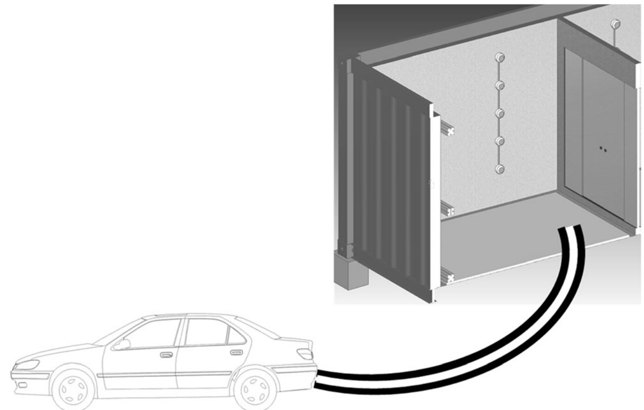

Fig. 2 Air contaminated introduced into the test room

Air decontamination tests

Counterfog® is a system producing a water-based fog with a specially designed nozzle whose droplets collide and aggregate to the particles in the surrounding air, therefore removing them out. Once the contaminated air in the test room was homogeneous, Counterfog® was activated for 30 s remaining closed during 30 min. The particle counter was continuously measuring the number of particles and droplets (not distinguishing between them). Temperature and humidity, as well as water flow were measured. After this experiment, the water (with the aggregated particles) deposited onto the floor was collected for analysis and characterization.

Less than 70 ml of water are used per cubic meter of air to be decontaminated. The power consumption is around 20 kW

Fig. 1 Fog dynamics laboratory. Test room before and after releasing the cleaning fog

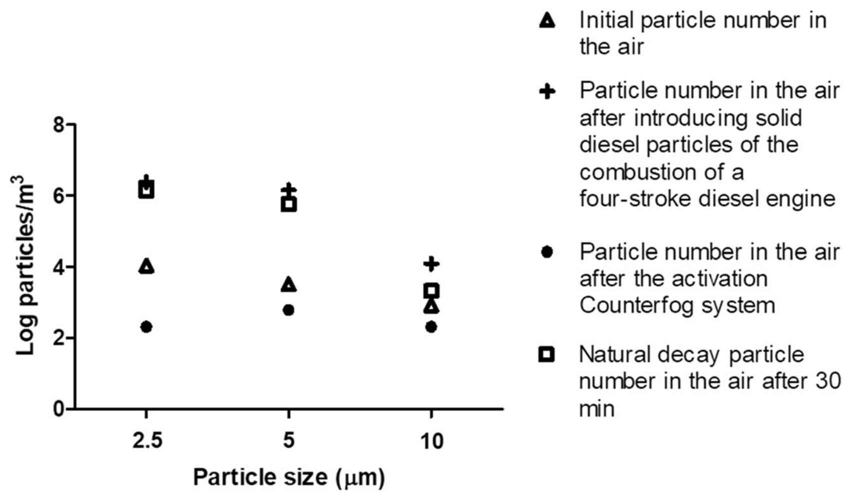

Fig. 3 Decimal logarithm of the number of particles in air per channel and cubic

what makes the specific energy consumed per cubic meter of air to be around 7.5 W h/m^3. The cost of the electrical energy used may be estimated to be 0.0015 EURO/m^3.

Analysis and characterization of the residue collected

Collected water samples after using the Counterfog® system, were submitted to a morphological study by scanning electron microscope (SEM), semi-quantitative analysis by energy dispersive X-ray analysis (EDXA) and a particle size distribution analysis by Mastersizer2000.

Results and discussion

Currently, there is increasing concern about the risks due to the inhalation of particles is suspension. Thus new mechanisms and technologies are being developed, either to prevent the emission of these particles or once they have been emitted to eliminate them from the air. The new system which is presented—Counterfog®—can be classified in the second type of technology. The results obtained (Fig. 3 and Table 1) indicate that the system allows to reduce the number of particles generated by the combustion of the Diesel in a percentage close to 100% in the case of particles of sizes 2.5 μm, 5 μm, and 10 μm diameter in a time not exceeding 30 min.

Also, the water deposited on the floor was collected; in Fig. 4, it is shown how the solid particles present in the air are deposited on the floor of the camera as a result of the fog. The dark gray color of the residues allows us to say that these particles are hydrocarbon residues. It is observed how the deposited solid particles tend to accumulate in certain regions of the surface and how the dimensions of the deposited residues are up to 40 cm allowing to assume the successful working of the Counterfog® system for this kind of situations. Figure 5 shows in detail of some residues by SEM, taken in secondary electron detector (SED) and in backscattered electrons detector (BSE). The particles' topography is showed in the images taken by SED and the atomic weight is showed by BSE. Figure 5a reveals particles bigger than 50 μm. When the particles were observed to a greater magnification, it can be seen that in fact those big particles are a group of particles that were agglomerated. Analyzing the BSE photographs, the majority of the particles shows a light color which means that the atomic weight is low.

The semi-quantitative analysis reveals that despite the results are not quantitative, the main elements are carbon and oxygen what corresponds with the expected composition of Diesel fuel combustion residue (Vogt et al. 2003; Wichmann 2007) (Table 2 and Fig. 6). Moreover, it coincides with the BSE images being the mayor component carbon which is atomic weight is small.

In addition, an analysis of the particle size distribution of different samples was carried out as exposed in Fig. 7. The tendency is not a Gaussian curve, but two different

Table 1 Percentage reduction of airborne particles

Particle size (μm)	After activation of Counterfog®	Natural gravitational decay
2.5	99.99 ± 1.10%	10.80 ± 1.1%
5.0	99.96 ± 0.80%	14.03 ± 0.8%
10.0	98.33 ± 0.40%	75.22 ± 0.4%

Fig. 4 Residues deposited on the floor of the camera after test

Table 2 Semi-quantitative analysis of the water with the residues

Element	Composition (%)	Deviation (%)
C	67.9	± 6.14
O	20.105	± 1.055
Na	0.565	± 0.125
Mg	0.63	± 0.16
Si	3.945	± 1.275
P	0.68	± 0.25
S	0.34	± 0.13
Cl	0.37	± 0.16
K	0.285	± 0.135
Ca	1.735	± 0.815
Fe	3.445	± 2.035

peaks can be observed in all the samples analyzed: (1) between 5 and 10 μm what is confirmed by the SEM analysis shown above; (2) between 100 and 1000 μm. Although, the particle size distribution is bigger than the described for emissions of Diesel engines by others authors (Bagley et al. 1998; Harris and Maricq 2001; Giechaskiel et al. 2009), it can be explained due we are not measuring the emissions, the measurement is made of the residues collected. The particulate matter, in the removing process from the air by Counterfog®, tent to agglomerate in the water droplets generated in the fog and also in the pool that is generated after the activation of the system.

The results obtained and shown above presented indication that the system-Counterfog® developed allows to reduce the number of solid particles from the combustion of the Diesel in a percentage close to 100% in the case of particles of sizes 2.5 μm, 5 μm, and 10 μm diameter in a time not exceeding 30 min.

This is an absolutely environmentally friendly system that does not produce any type of residue during its implementation. This supposes its possibility of application in all type of situations and places including those with presence of civil population, since its application is innocuous for the human being to base its operation in the use of both water and air. This method develops a novel form for the decontamination of suspended airborne particles of Diesel, since the current methods are very scarce and do not allow their implementation in large buildings or with the presence of civil population. Moreover, it could be of great interest for its implementation in outdoor spaces and for the cleaning of other types of particles, such as chemical, radiological, or biological agents, being them under study.

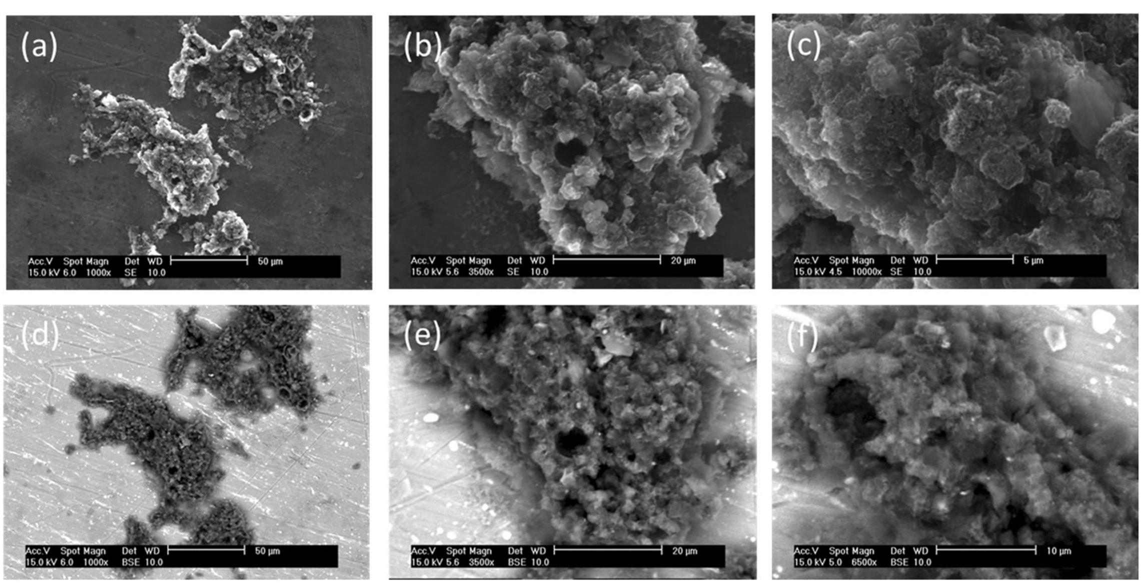

Fig. 5 SEM images from the residues collected from water. **a** SED photography taken at 1000 magnifications. **b** SED photography taken at 3500 magnifications. **c** SED photography taken at 10,000 magnifications. **d** BSE photography taken at 1000 magnifications. **e** BSE photography taken at 3500 magnifications. **f** BSE photography taken at 10,000 magnifications

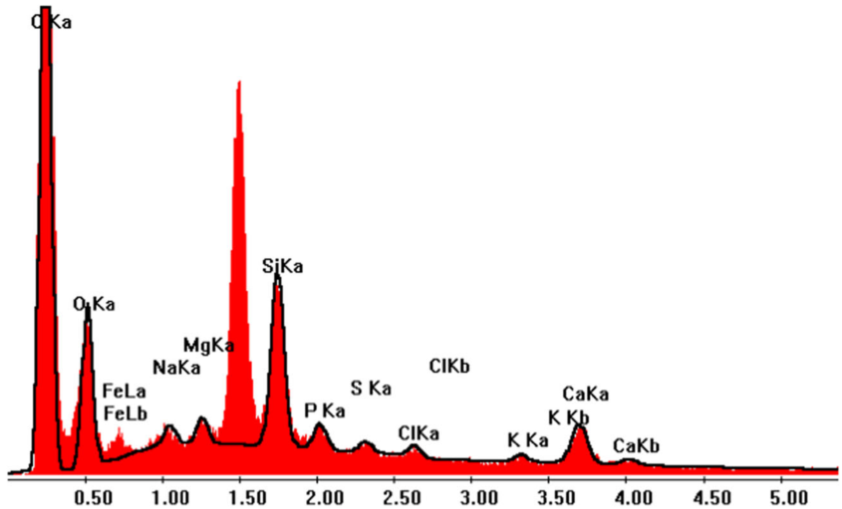

Fig. 6 Semi-quantitative analysis of the residue collected

The fact that all walls, ceiling, and floor show soot waste and water demonstrates that the washing effect of Counterfog® is only in a small fraction related to gravity. The main washing out power comes from the cone fog dynamics itself dragging and accelerating air into the fog cone.

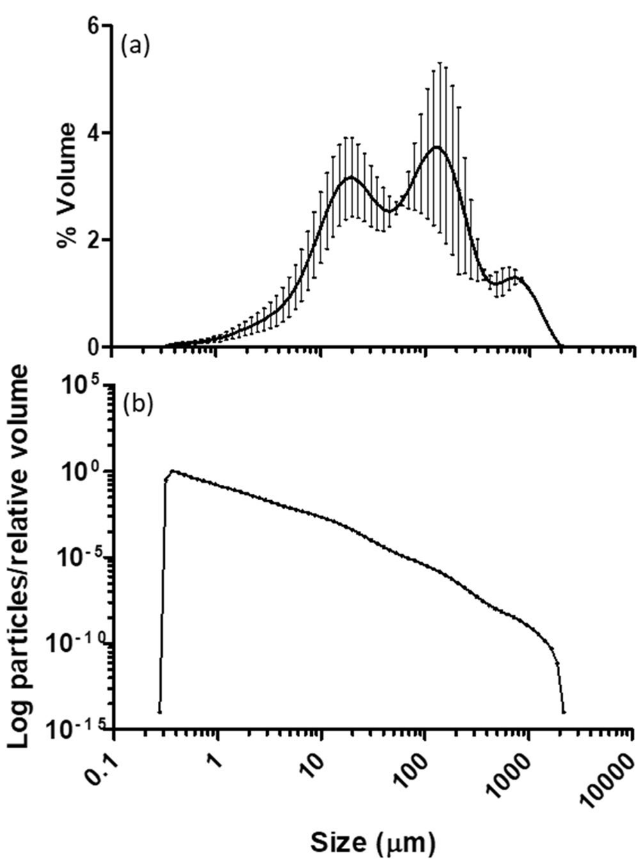

Fig. 7 **a** Mean and standard deviation distribution of volumes for each particle size. **b** Particles number of each size attending to the relative volume

Conclusions

The new technology for decontamination of airborne particles in air called Counterfog® has demonstrated to remove airborne PM10 originated from a Diesel engine by 2 orders of magnitude, PM 5 by 3 orders of magnitude, and PM2.5 by 4 orders of magnitude using just compressed air and water. As the energy used for this process can be electrical and therefore quite convenient for green energy with an estimated operation cost of just 0.0015 EURO/m^3, this technology provides a unique and effective tool for cleaning air in cities, improving air quality, and decreasing respiratory diseases among population in large cities.

Funding information This work has been funded by the FP7-SEC-2012-1 program of the EU Commission under grant number 312804.

References

Allaby M (2003) Fog, smog and poisoned rain. Facts on File, Inc., New York

Bagley ST, Gratz LD, Johnson JH, McDonald JF (1998) Effects of an oxidation catalytic converter and a biodiesel fuel on the chemical, mutagenic, and particle size characteristics of emissions from a diesel engine. Environ Sci Technol 32:1183–1191

Casarrubios JSG, Llerena-Aguilar FJ, Pérez-Díaz JL (2018) Fog dynamics. In: Malizia A, D'Arienzo M (eds) Enhancing CBRNE safety & security: proceedings of the SICC 2017 conference. Springer, Cham

Dockery DW, Pope CA, Xu XP, Spengler JD, Ware JH, Fay ME, Ferris BG, Speizer FE (1993) An association between air-pollution and mortality in 6 United- States cities. New Engl J Med 329:1753–1759

European Environment Agency (EEA) 2012 Climate change, impacts and vulnerability in Europe ISSN 1725-9177 Report No 12/2012

European Environment Agency (EEA) 2017 Air quality in Europe ISSN 1725-9177 Report No 13/2017

Fenger J, Tjell JC (2009) Air pollution-from local to a global perspective. RCS Publishing Polyteknisk, Forlag

Giechaskiel B, Alföldy B, Drossinos Y (2009) A metric for health effects studies of diesel exhaust particles. J Aerosol Sci 40:639–651

Greenfield SME (1956) Rain scavenging of radioactive particulate matter from the atmosphere. J Meteor 14:115–125

Grigoratos T, Martini G (2014) Brake wear particle emissions: a review. Environ Sci Pollut Res 22(4):2491–2504

Harris SJ, Maricq MM (2001) Signature size distributions for diesel and gasoline engine exhaust particulate matter. J Aerosol Sci 32:749–764

Lucking AJ, Lundbäck M, Barath SL, Mills NL, Sidhu MK, Langrish JP, Boon NA, Pourazar J, Badimon JJ, Gerlofs-Nijland ME, Cassee FR, Boman C, Donaldson K, Sandstrom T, Newby DE, Blomberg A (2011) Particle traps prevent adverse vascular and prothrombotic effects of diesel engine exhaust inhalation in men. Circulation 123:1721–1728. https://doi.org/10.1161/CIRCULATIONAHA.110.987263

Martín-Pérez T, Llerena-Aguilar FJ, Pérez-Serrano J, Copa-Patiño JL, de Carranza JS, Orellana-Muriana JM, Pérez-Díaz JL (2018) Eco-friendly air decontamination of biological warfare agents using "counterfog" system. In: Malizia A, D'Arienzo M (eds) Enhancing CBRNE safety & security: proceedings of the SICC 2017 conference. Springer, Cham

Nel A (2005) Air pollution-related illness: effects of particles. Science 308:804–806

Pérez-Díaz JL, Qin Y, Ivanov O, Quiñones J, Stengl V, Nylander K, Hornig W, Álvarez J, Ruiz-Navas EM, Manzanec K (2018) Fast response CBRN high-scale decontamination system: COUNTERFOG. In: Malizia A, D'Arienzo M (eds) Enhancing CBRNE safety & security: proceedings of the SICC 2017 conference. Springer, Cham

Pope CA, Thun MJ, Namboodiri MM, Dockery DW, Evans JS, Speizer FE, Heath CW (1995) Particulate air-pollution as a predictor of mortality in a prospectivestudy of US adults. Am J Respir Crit Care Med 151:669–674

Vogt R, Kirchner U, Scheer V, Hinz KP, Trimborn A, Spengler B (2003) Identification of diesel exhaust particles at an autobahn, urban and rural location using single-particle mass spectrometry. J Aerosol Sci 34:319–337

Wichmann HE (2007) Disel Exhaust Particles. Inhal Toxicol 19:241–244

World Health Organization (WHO) 2013 Health effects of particulate matter. Convention on Long-Range Transboundary Air Pollution ISBN 978 92 890 0001 7