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Soil Air Water

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Research Article

Innovative Germicidal UV and Photocatalytic System Dedicated to Aircraft Cabin Eliminates Volatile Organic Compounds and Pathogenic Micro-Organisms

Air quality on aircraft cabins has become a major public health issue due to the increasing number of air travels since few decades. Exposure to volatile organic compounds (VOC) and micro-organisms is a major concern for human and animal welfare in indoor confinements and especially in aircraft cabins. Here we present an innovative air purification system based on the association of UV-C and photocatalysis. The SAVAB project is aiming at a higher decontamination degree of aircraft cabin air, thus improving health and comfort standards of aircraft crew and passengers. We show a degradation of irritating/noxious VOC such as formaldehyde, toluene, benzene, acetone, which are major pollutants of the aircraft cabins according the NF EN 4618 standard. In the same study, we also demonstrate the inactivation of pathogenic Influenza virus, adenovirus and pathogenic bacteria such as *Legionella pneumophila*, *Burkholderia cepacia*, *Streptococcus pneumoniae*, and *Pseudomonas aeruginosa*. This innovative system demonstrates its ability to improve air quality in indoor confinements of travel-motorized units such as aircraft cabins and could be applied in hospital environments.

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1 Introduction

Due to the increasing number of air travels during the past decades, air quality on aircraft has become an important public health issue [1, 2]. Concerned about energy savings, aircraft manufacturers started to integrate air recycling systems and thus, filtering equipment since 1980. Planes have become an important vector of disease spreading between countries [3–5]. Besides, commercial aircraft crews (pilots, flight attendants, etc.) address more complaints about the air quality than office workers, due to differences experienced in these two environments [6].

Given the large number of passengers in an aircraft cabin, high concentrations of particles (dust, thin fibers, skin particles), bacteria (up to 30 000 bacteria per minute per passenger can be released from skin scales into the cabin environment), fungi, viruses, and volatile organic compounds (VOCs) carrying odors [7] are encountered. Thus, exposure to one or several indoor air pollutants may lead to various adverse health effects such as headaches, loss of memory, dizziness, etc. [8, 9].

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Abbreviations: **CFU**, colony-forming unit; **HEPA**, high efficiency particulate air; **PCO**, photocatalytic oxidation; **ppbv**, part per billion by volume; **ppmv**, part per million by volume; **VOC**, volatile organic compound

Indeed, the air we breathe in commercial aircraft cabins, although carefully filtered and partially regenerated, is also contaminated by a variety of chemical pollutants, harmful for people health and source of discomfort (odors, irritations, etc.). Numerous organic compounds can be released in air cabin from the cabin interior components such as fabrics and furnishings, including chemicals from cleaning supplies or from food and beverages [10, 11]. They can also be emitted by lubricants, fuel, or combustion gases, abundant in aircraft parking positions. VOCs can also be brought by the occupants themselves (bioeffluents), their clothing and luggage [10]. VOCs can be responsible of odors and a number of them are known to have disturbing effects such as headaches, throat and noise irritations, etc.

When inhaled, ozone can aggravate chronic diseases such as bronchitis and asthma [12]. Two studies among passengers suspected that the high prevalence of nose, eye, and throat symptoms may be due to ozone exposure [13, 14]. Ozone may also react with surfaces and generate volatile by-products (aldehydes, acetone, nonanal, etc.) that can be irritant and of potential concern for the health of passengers and crew [12, 15, 16]. Indeed, irritative effects and inflammatory responses were observed when formaldehyde was inhaled at a low dose [17]. Recent test programs have been run to identify and quantify organic pollutants in aircraft cabins among different flights [2, 18]. These studies enhance the real interrogation about the influence of pollutants found in enclosed spaces on general health [1]: compounds such as carbon monoxide, carbon dioxide, simple carbon compounds (C6–C16), halogens, and carbonyls.

Highest concentrations of VOCs have been detected during take-off and landing [2, 18].

Mangili and Gendreau [5] reviewed the risks of airborne infection spreading among the passengers inside aircraft cabins from various respiratory outbreaks and concluded that risk of in-flight infection disease transmission was very high. Commercial airlines are a suitable environment for the spread of pathogens carried by passengers or crew. The use of appropriate filters and correct air recirculation in the plane reduces the risk of infection. In general, high efficiency particulate air (HEPA) filters used on commercial airlines have a 99.97% particle-removing efficiency at 0.3 μm [6]. These filters remove dust, vapors, bacteria, fungi, and viral particles that spread by droplet nuclei. Although the safety of HEPA in protection against viruses has been questioned, a more serious concern is the absence of legislation obliging their use in most countries. As a consequence, HEPA filters are not used on 15% of flights carrying more than 100 passengers in the USA; this percentage is considerably higher in small planes that undertake local flights [4].

Improving air purification techniques is one approach to avoid aircraft cabin pollution problems. The aim of this study was to develop a system for VOC and micro-organisms removal in aircraft cabin, safe for the environment and harmless for people, in order to ensure health and comfort to passengers and cabin crews and to limit the spreading of infectious diseases.

The photocatalytic oxidation (PCO) has been shown to be an effective process for air disinfection and removal of biological and chemical pollutants. Numerous studies were conducted on air photocatalysis disinfection and have demonstrated that titanium dioxide coupled with UV irradiation could be applied to degrade VOCs [19, 20] without significant energy input [21] and to eliminate micro-organisms [22–25]. Germicidal UV (UV-C) is commonly used to treat water and destroy micro-organisms. However, its effects on some micro-organisms are limited [26, 27].

The anti-virus and anti-bacteriological system project (SAVAB) is aiming at a higher decontamination degree of aircraft cabin air, thus improving health and comfort standards of aircraft crew and passengers, by reduction of irritating/noxious VOCs and elimination of pathogenic micro-organisms using Aelorve technology. The aim of the project is to develop a system providing indoor air treatment in aircraft at affordable acquisition and maintenance cost.

Aelorve SAS, leader of the SAVAB project, has developed a unique industrial air-treatment solution registered as the Aelorve-System. This innovative patented technology (EP 07 019 639-9) combines germicidal UV-C and PCO. Several VOCs (acetone, formaldehyde, etc.) known to be present in aircraft cabins and to cause adverse effects (headaches, eye irritation, nausea, etc.) were selected (Tab. 1). Similarly, micro-organisms may play a role in respiratory infection by the spreading of fine particle aerosols. These chemical and biological targets were then applied to the Aelorve purification system in order to determine its effectiveness in degrading the pollutants and the absence of by-products.

The results of these tests are presented and discussed to examine the efficiency of experimental photocatalytic reactors in air disinfection.

2 Materials and methods

2.1 Photocatalytic experimental unit

The system is a cylindrical reactor, including specific internal wall shape, as described in the patent EP 07 019 639-9. Internal walls are coated by a commercial TiO_2 (PC500 from Millenium and P25 from Evonik) photocatalytic gel surrounding an ozone-free mercury lamp (UV-C Creator Lighting CUH18L 18W and CUH35L 35W). Specific optimization consists in internal wall shapes design, photocatalytic gel constitution, and the know-how of its application. Micro-organisms and chemical molecules pass through the reactor and are exposed to the effects of both degradation means. Minimum residence time was evaluated between 0.06 and 0.13 s depending on the flow rate.

XP series reactors are consumable units, designed to be integrated in air treatment equipment, air ducts, or remote portable devices. The efficiency of XP series reactors in air disinfection was studied in a one-pass flow tunnel for both bacteria and viruses, and in an experimental closed chamber for VOCs.

Different experimental reactors were tested (XP01 and XP02). The XP02 reactor is an enhanced and optimized version of the XP01 reactor: improved coating and UV power (60–105 $\mu W/cm^2$). XP01 and XP02 reactors are 300 mm long and 100 mm in diameter.

2.2 VOCs

2.2.1 Selected VOCs

All chemicals were obtained commercially with a purity of >99% and used without further purification. The used VOC were the following:

Table 1. Representative compounds selected according to the NF EN 4618 standard (aerospace standard for indoor air quality in aircraft cabins)

Compound	Pathological symptoms according to material safety data sheet (MSDS)	Concentration measured in aircraft cabins (ppbv) [2, 10]
Formaldehyde	Toxic if inhaled	12.2
Acetaldehyde	Tearing, irritation, nausea, vomiting, chest pain, difficulty breathing, headache, drowsiness, lung congestion	17.2
Acetone	Hazardous in case of inhalation, vapors inhalation may cause drowsiness and respiratory tract irritations	84.2
Toluene	Eye irritation, nausea, headache, dizziness	45.1
Benzene	Carcinogenic effects, eye and skin irritations, nausea, vertigo, headache	1.4
Dichloromethane	May cause irritation to the respiratory system, carcinogenic effects	5.8
Acrolein	Tissue damage particularly on mucous membranes of eyes, mouth and respiratory tract, coughing, choking, shortness of breath	1.7
2-Butanone	May be toxic to gastrointestinal tract, upper respiratory tract, central nervous system (CNS)	8.5
Ozone	Dryness, coughing, irritations, headache, fatigue	30.6

acetone (Sigma–Aldrich, St. Louis, MO, A.C.S., ≥99.5), *n*-heptane (Acros, 99 + % pure), acetaldehyde (Fluka, ≥99.5%), toluene (Scharlau, HPLC grade), *o*-xylene (Fluka, puriss p.a., >99%), 2-butanone (Acros, 99+%), acrolein (Fluka, puriss ≥99.0%), formaldehyde (Sigma–Aldrich, 37 wt% in water, A.C.S reagent), benzene (Aldrich, 99.9+% HPLC grade), dichloromethane (Sigma–Aldrich, HPLC ≥99.9%). Moreover, ozone obtained from oxygen plasma, was also introduced.

Different VOC mixtures were used in the experiments their composition is detailed in Tab. 2.

2.2.2 Chamber experiments

The analyses were performed in agreement with the newly published AFNOR standard method related to the VOCs photocatalytic mineralization.

The reactor was inserted in a 1.2 m^3 closed chamber made of poly (methyl methacrylate) (Fig. 1). A fan added to the reactor induced a known flow (70–75 m^3/h) measured with a Testo anemometer and a sensor of 10 mm diameter. A mixing fan was placed in the chamber in order to homogenize the air.

The chamber was supplied with purified and humidified air overnight with the reactor switched on, in order to make sure that the system had been cleaned with clean air before taking any measurement. There is no CO_2 in the initial air mixture and the experiments were carried out at room temperature.

Pollutant mixture was introduced in the chamber with a syringe and homogenized in the chamber by action of the mixing fan, with the reactor turned off. After stabilization of the air composition, the reactor was then switched on again and analytical monitoring of the mixture was made using GC with a photoionization detector (EPA) by on-line samplings on a regular basis during experiments. This analysis is efficient for concentrations comprised between sub-ppbv (part per billion by volume) and ppmv (part per million by volume), without pre-concentration.

Cartridge samplings were performed before pollutants introduction, in the middle of the test and at the end of test. Aldehydes were analyzed by adsorption on a DNPH cartridge followed by chemical desorption and HPLC (Waters) analysis and compared to a standard list. The other compounds were adsorbed on specific cartridges (Tenax or Chromosorb) and were analyzed using thermal desorption

Table 2. Degradation rate of VOCs with XP01 and XP02 reactors on different concentrations

	Reactor XP01		Reactor XP02	
Compound	Degradation rate (ppbv/min) (1000 ppbv)	Degradation rate (ppbv/min) (250 ppbv)	Degradation rate (ppbv/min) (1000 ppbv)	Degradation rate (ppbv/min) (almost 200 ppbv)
Formaldehyde	10.79	9.00	–	2.91
Acetaldehyde	7.28	–	6.73	2.20
Acetone	2.07	2.06	4.95	1.50
n-Heptane	1.70	1.44	3.42	–
o-Xylene	–	7.40	22.02	–
Toluene	3.17	2.77	7.64	3.92
Benzene		1.10		1.56
Dichloromethane[a)]				0.30
Acrolein				10.00
2-Butanone				5.69
Ozone[b)]				15.36

[a)] Dichloromethane was partially degraded.
[b)] Ozone was tested in the absence of the other compounds.

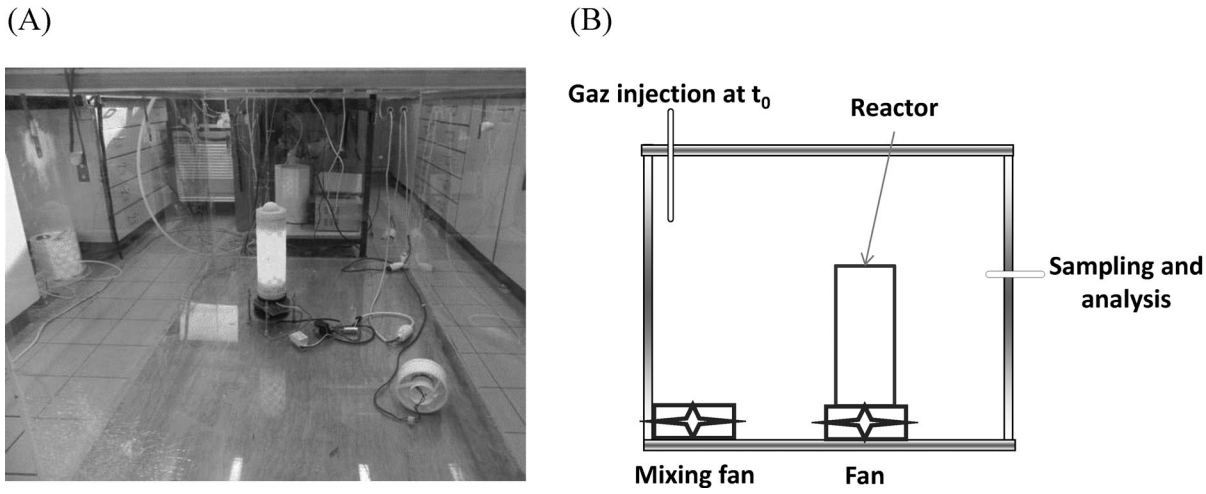

Figure 1. (A) Photograph of the closed chamber of 1.2 m^3 used for chemical experiments. (B) Scheme of the experimental closed chamber of 1.2 m^3 used for the chemical assays.

combined with GC/MS (V&F). The analytical methods were used according to the ISO 16000 standard for the air analysis. Sampling rates for DNPH cartridges were 1 L/min for 15 min. Sampling rate for Tenax or Chromosorb cartridges were comprised between 20 and 150 mL/min for 10 min.

Tests were done at 200 or 250 and 1000 ppbv/pollutant, with airflows in the device comprised between 70 and 75 m^3/h at 22°C and 50% relative humidity (according to AFNOR standard parameters). Temperature and relative humidity were monitored all along the tests, that lasted until total degradation of the pollutants. The 1000 ppbv/pollutant concentration allowed the analytical monitoring by microcatharometer of the CO_2 formation due to the pollutants mineralization. Levels of the concentrations were higher than those typically found in aircraft cabins because the aim of this work was to prove the degradation of the type of compounds mixtures and to determine the by-products. Initial degradation rates (ppbv/min) were calculated and are reported in Tab. 2.

Concerning the ozone, the experiment was monitored with a specific sensor (Gas Alert Micro 5 PID from BW technologies).

The stability of VOC concentration and the release of VOCs from the closed chamber were investigated without the experimental photocatalytic reactor during 8 h. A variation of lower than 10% was observed.

2.3 Biological materials

2.3.1 Micro-organisms culture and conditioning

Pathogenic bacteria were chosen according to several characteristics: (i) their pathology should be associated to pneumonia symptoms in humans, (ii) they should be airborne or aerosol stable bacteria, and (iii) some of them should belong either to Gram-positive or Gram-negative bacteria. The latter characteristic is related to their membrane composition and organization. To this end we chose four bacteria: *Streptococcus pneumoniae*, a Gram-positive pathogenic bacterium causing pneumonia, *Legionella pneumophila*, a Gram-negative pathogenic bacterium responsible of the Legionnaire's disease, *Pseudomonas aeruginosa*, a Gram-negative pathogenic bacterium that colonizes lungs, the urinary tract and kidneys and finally *Burkholderia cepacia*, a Gram-negative bacterium that causes pneumonia in immunocompromised individuals with underlying lung disease such as cystic fibrosis or chronic granulomatous disease.

Pathogenic viruses were chosen according to both structural organization (enveloped and non-enveloped) and airborne transmission. Influenza virus is an enveloped virus that caused a common contagious airborne illness. Symptoms like sneeze, cough provided small particles into the air. Two subtypes of Influenza A virus were selected for this study: A/Lyon/969/2009 pandemic H1N1 and A/Moscow/10/99 H3N2 viruses. Adenoviruses are non-enveloped icosahedral viruses composed of a nucleocapsid conferring an increased resistance against environment. The adenovirus transmission occurs by expectoration, by contact with an infected person, or by virus particles left on objects such as towels and faucet handles.

S. pneumoniae were grown on blood agar (bioMérieux) for 36 h at 37°C. Stock solution was streaked on blood agar plates and incubated for 36 h at 37°C. Final bacterial concentration was at 10^9 bacteria/mL in 300 mL PBS. Bacteria were quantified by colony-forming unit (CFU) counting. *L. pneumophila* were grown on coal agar (bioMérieux) for three days at 37°C. Colonies were then collected from the plates to establish a stock solution. This solution was streaked on coal agar plates and incubated de novo at 37°C for three days. After three days, bacteria were collected to prepare the final solution, which was used for nebulization (300 mL, 10^9 bacteria/mL). Bacteria were quantified by CFU counting. *B. cepacia* were grown on blood agar (bioMérieux) medium for 24 h at 37°C to obtain the optimal bacteria quantity. For nebulization, the stock solution was streaked on blood agar plates and incubated for 24 h at 37°C. Colonies were then collected and solubilized in order to prepare the final 300 mL PBS solution containing 10^9 bacteria/mL. Bacteria were quantified by CFU counting. *P. aeruginosa* were grown on blood agar (bioMérieux) for 24 h at 37°C. This stock solution was streaked on blood agar plates and incubated as previously described for 24 h. Colonies were harvested and resuspended in 300 mL PBS (10^9 bacteria/mL). Bacteria were quantified by CFU counting.

A/H1N1pdm2009 and A/Moscow/10/99 H3N2 influenza viruses were cultivated on Madin–Darby Canine Kidney (MDCK) cells for three days with 5% CO_2 at 37°C. MDCK cells (ATCC, CCL34) were passaged twice weekly in serum free Ultra-MDCK medium (Cambrex Bioscience, Walkersville, MD) supplemented with penicillin (225 U/mL), streptomycin (225 μg/mL; Cambrex Bioscience) and 2 mM L-glutamine (Sigma–Aldrich). A549 cells were maintained in Dulbecco's modified Eagle's medium supplemented with 2 mM L-glutamine (Sigma–Aldrich), supplemented with 10% fetal calf serum and, penicillin (225 U/mL) and streptomycin (225 μg/mL) (Cambrex Bioscience). All cells were maintained with 5% CO_2 at 37°C [28]. Viral supernatants were harvested, purified, and concentrated by saccharose gradient and ultracentrifugation [29]. Influenza viruses were prepared in 200 mL PBS solution and virus titration was realized as described by Moules et al. [30] (10^8 and 10^9 $TICD_{50}$/mL for H3N2 and H1N1 viruses, respectively).

Wild-type adenovirus 5 (wt Ad5) grown by infection of A549 cells for 38 h at 37°C with 5% CO_2. Wild-type adenovirus 5 was purified in order to prepare the final 200 mL PBS solution. Growing, purification, titration, and storage were as described previously (10^9 $TCID_{50}$/mL) [31].

The sensitivity of viral titer quantifications was 1.3 log $TCID_{50}$/mL.

2.3.2 Experimental system

The system consisted of a one-pass tunnel containing the photocatalytic reactor and a nebulization chamber (Fig. 2). Air samples could be taken before and after the reactor through the sampling ports using a vacuum pump and then focused onto 5 mL of collection fluid (Fig. 2). For safety, the entire system was installed in BSL2/BSL3 laboratories with the entry and exit of the flow system located inside biological safety hoods within the laboratory. Samplers were also located inside safety hoods to determine upstream and downstream outlet airborne levels of micro-organisms. Micro-organisms solutions were dispatched equitably between two nebulizers (BGI Instruments, Waltham, USA). Nebulizers were then placed within the nebulization chamber under 1.5 bar pressurized air and placed at two different angles within the box. For the saturation, the principal air pipe, allowing air to go through the reactor, was closed. Moreover, to prevent an over-pressurization, a secondary pipe of the nebulization chamber was open and placed under a second microbiology hood. The saturation of the nebulization chamber consisted of 15–20 min of nebulization associated with air flow mixture. When saturated, the principal air pipe of the nebulization chamber was open (the secondary pipe closed) and samples were collected (air speeds: 1.5 or

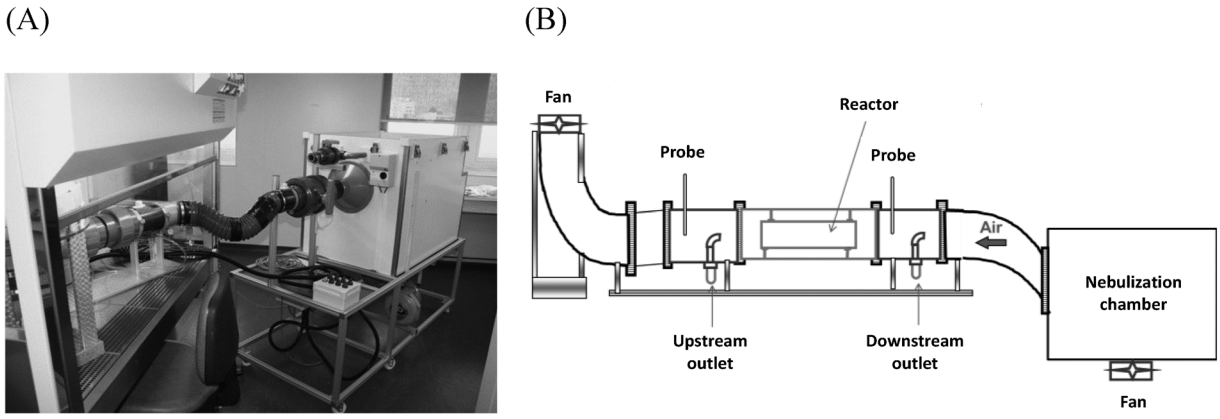

Figure 2. (A) Photograph of the single-pass experimental setup. (B) Scheme of the single-pass experimental setup used for the assays.

3.5 m/s) in 50 mL Falcon tubes (Becton-Dickinson) in 5 mL of PBS before and after exposure to the reactor as the pumps were turned on. Air speeds were measured with an air velocity sensor (KIMO) placed between the nebulization chamber and the downstream outlet.

Experiments were conducted as follow. First, we evaluated the bacteria and virus loss due to nebulization and impaction within the experimental system. Experimentations were done with the photocatalytic reactor switched off at two different air velocities (1.5 and 3.5 m/s). Then, single-pass efficiency values were determined by using the above protocol for all micro-organisms at two different air velocities with the photocatalytic reactor switched on.

A blank assay was performed before each experiment in order to ensure that no microorganism remained within the reactor.

3 Results

3.1 Efficiency on VOCs

Based on aircraft air cabin studies [1, 2], 40 different compounds known to be noxious and to cause pathological symptoms such as headaches, vertigo, or nausea were listed and were categorized into 22 families of chemical compounds. Nine representative compounds were selected according to the NF EN 4618 Standard (aerospace standard for indoor air quality in aircraft cabins; Tab. 1): acetone, 2-butanone, acetaldehyde, acrolein, formaldehyde, benzene, toluene, dichloromethane, and ozone. The degradation by the Aelorve system was tested on a mixture of these compounds to know about its degradation and the formation of by-products. Ozone was also tested but without any other compounds.

In a first time the Aelorve system was tested and improved on a mix made of acetone, toluene, *n*-heptane, *o*-xylene, formaldehyde, and acetaldehyde. The first test made with the XP01 reactor at 1000 ppbv/pollutant showed a total disappearance of all the pollutants after a 10 h irradiation (Tab. 2).

The highest to lowest degradation rates were measured for formaldehyde, acetaldehyde, toluene, acetone, and then *n*-heptane. Similar results were measured using the XP01 reactor (Tab. 2) on a gas mixture at a lower concentration (250 ppbv/pollutant for 4 h) where acetaldehyde was replaced by *o*-xylene (Fig. 3).

The quantity of resulting CO_2 confirmed that the mineralization was complete and that the VOC degradation was due to photocatalytic reaction (data not shown). The analysis of the different adsorption cartridges did not show the formation of any by-product: neither aldehydes nor aromatic and aliphatic derivatives.

The TiO_2 coating formulation and the power of the UV lamp were modified in each version of the reactor. The coating included PC500 from Millenium in the reactor XP01, then P25 from Evonik in the reactor XP02. The irradiance was increased from 60 $\mu W/cm^2$ (lamp CUH18L 18W for reactor XP01) to 105 $\mu W/cm^2$ (lamp CUH35L 35W for reactor XP02) to improve the Aelorve system efficiency. Table 2 shows the XP02 reactor efficiency on VOCs at a concentration of 1000 ppbv/pollutant during 4 h. By improving the reactor from version XP01 to version XP02, the degradation rate increased for all the pollutants except acetaldehyde (Tab. 2).

This improved system was then tested on a specific mix of VOCs, which were selected for being the most representative ones found in aircraft cabins at 200 ppbv/pollutant for 11 h.

The detection limits of the analytical used techniques led us to choose higher concentrations than the one measured in aircraft cabins (Tab. 1). Each compound has totally disappeared during the test, except dichloromethane. Its degradation began after all the other compounds were eliminated and its degradation rate was very low (Tab. 2).

Acrolein had the greatest degradation rate. Analyses of the cartridges by HPLC showed no significant formation of by-products during this experiment.

An efficiency test performed on ozone alone at 1000 ppbv/pollutant with the XP02 reactor showed that the Aelorve system degraded

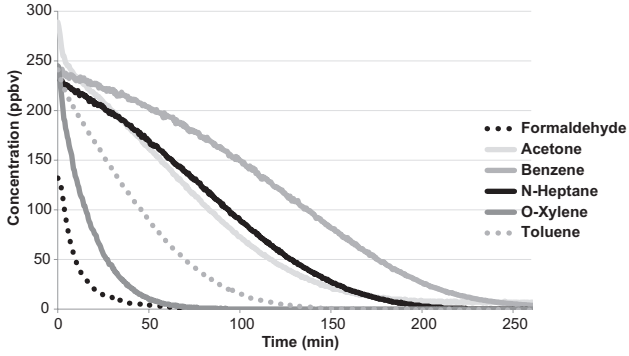

Figure 3. Evolution of VOC concentration of a mixture of acetone, benzene, *n*-heptane, *o*-xylene, and formaldehyde (each VOC concentration near 250 ppbv except formaldehyde).

ozone. Natural degradation rate was estimated at 2.28 ppbv/min while the degradation rate reached 15.36 ppbv/min when the reactor was running. Furthermore, UV-C lamps used by Aelorve were tested alone and showed no ozone emission during a specific experiment.

3.2 Biological efficiency

3.2.1 Elimination efficiency on pathogenic bacteria

We tested the ability of bacteria to survive when the Aelorve system was switched on. First, we observed that air velocity did not significantly influence bacteria survival within collected samples (Figs. 4 and 5). We also observed that nebulization by itself, without any photocatalysis, induced between 1 and 3 log of bacterial concentration loss (Figs. 4 and 5). A concentration between 10^8 and 10^6 CFU/mL was expected after nebulization.

When the XP01 reactor was switched on, most of *L. pneumophila* and *B. cepacia* were inactivated after exposure (Fig. 4) as we observed 3.5 log and 3 log of bacteria loss, respectively. However, *S. pneumoniae* and *P. aeruginosa* seemed to be more resistant as we could observe 1 log and 2 log of bacterial clearance, respectively (Fig. 4).

We tested the XP02 reactor using two bacteria concentrations: the maximum efficiency of the reactor against an extremely contaminated air (high concentration: 10^9 CFU/mL) while a lower concentration (10^6 CFU/mL) was the maximum concentration for which all bacteria were eliminated. Losses of 3 log for *L. pneumophila* and *B. cepacia*, 4 log for *S. pneumoniae*, 4.5 log (speed 1.5 m/s), and 5 log (speed 3.5 m/s) for *P. aeruginosa* were observed at high bacteria concentration (Fig. 5).

3.2.2 Elimination efficiency on viruses

First, we controlled that neither air velocity nor XP01 reactor shapes significantly influence virus survival. At 1.5 m/s, we showed that the XP01 reactor (UV OFF) was responsible to the viral loss of 0.8, 0.6 and 0.7 log $TCID_{50}$/mL for H3N2, H1N1 viruses and adenovirus, respectively (Fig. 6). For influenza viruses, 4.0 and 3.7 log $TCID_{50}$/mL have been collected in the air stream after the reactor for H3N2 and H1N1 viruses, respectively. For adenovirus, a total of 4.1 log $TCID_{50}$/mL has been collected. When we increased the air velocity through the system up to 3.5 m/s, the viral loss due to the reactor switched-off increased to 1 log $TCID_{50}$ for H3N2 and H1N1 viruses, respectively, whereas we observed a decrease of viral loss for adenovirus corresponding to 0.5 log $TCID_{50}$/mL (Fig. 6).

In a second time, we evaluated the efficiency of the different photocatalytic reactors on virus stream. The first tests were done on the XP01 reactor. The results showed that the device was able to reduce the viral load corresponding to a decreased of 3.5 and 2.9 log $TCID_{50}$/mL for H3N2 and H1N1 viruses, respectively, at 1.5 m/s and a decrease of 1.7 and 1.6 log $TCID_{50}$/mL, respectively, at 3.5 m/s (Fig. 6). Tests on adenovirus suggested a lower efficiency of this device at 1.5 m/s by a decreased of infectious titer of 1.3 log $TCID_{50}$/mL (Fig. 6) and at 3.5 m/s by a decreased of 0.8 log $TCID_{50}$/mL.

Resistance of adenovirus against the first device led us to perform other tests with the enhanced reactor (XP02). We first evaluated this new device (UV OFF) and effects of air velocity on H3N2 virus and adenovirus by measuring the gap between upstream and downstream outlet (Fig. 7). Results revealed that loss of viral load by the experimental system at 1.5 m/s was 1.0 and 0.4 log $TCID_{50}$/mL for H3N2 virus and adenovirus, respectively. The impact of the device on viruses increased to 1.5 and 0.9 log $TCID_{50}$/mL, respectively, for H3N2 virus and adenovirus at 3.5 m/s. When we enabled the XP02 reactor, infectious titers of adenovirus showed an attenuation of 2.5 and 1.5 log $TCID_{50}$/mL at 1.5 m/s and at 3.5 m/s, respectively (Fig. 7). As a control, we checked that the XP02 reactor was efficient to destroy influenza viruses with an attenuation of 4.0 and 2.5 log $TCID_{50}$/mL at 1.5 and 3.5 m/s, respectively.

4 Discussion

An aircraft cabin environment is different in several ways from other indoor environments such as homes or offices. This is mainly due to high occupant density, confined space, limited ventilation, prolonged exposure times, and underpressurization at typical cruising altitude [11, 16, 32]. The relative humidity in aircraft cabins is usually <20% [33] and high ozone levels are frequently experienced [16].

The system technology is based on the combination of UV-C and photocatalysis, which consists in a catalyst, TiO_2, generating oxidative radicals under photon activation. Active sites and thus, oxidative radicals produced are present on coated surface. The

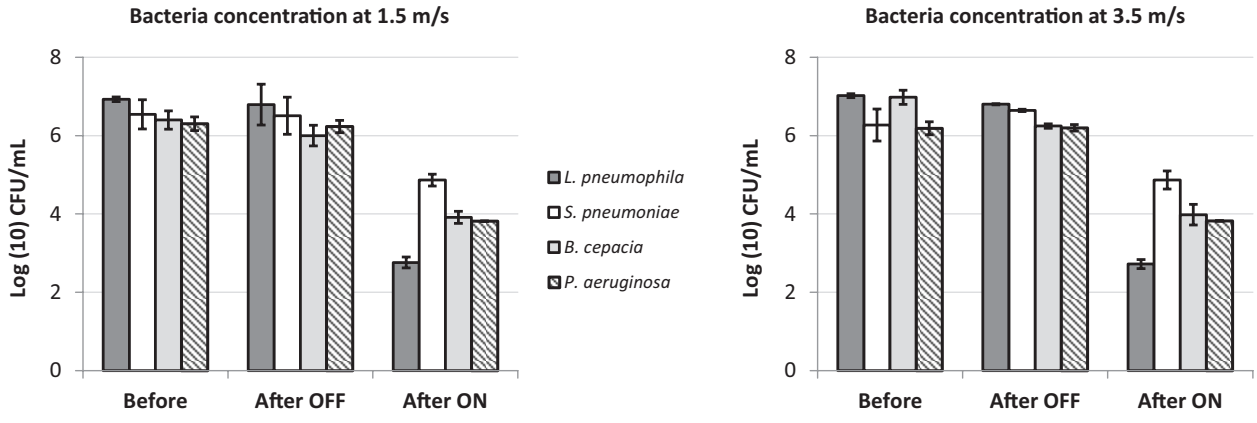

Figure 4. Bacteria concentration before and after exposure to XP01 reactor. The experiments were realized at two different speeds (1.5 and 3.5 m/s) and with chamber saturation. Results were analyzed before and after exposure to the reactor and expressed in CFU/mL. The «After OFF» histograms represent the bacteria concentration after the reactor while it was turned OFF.

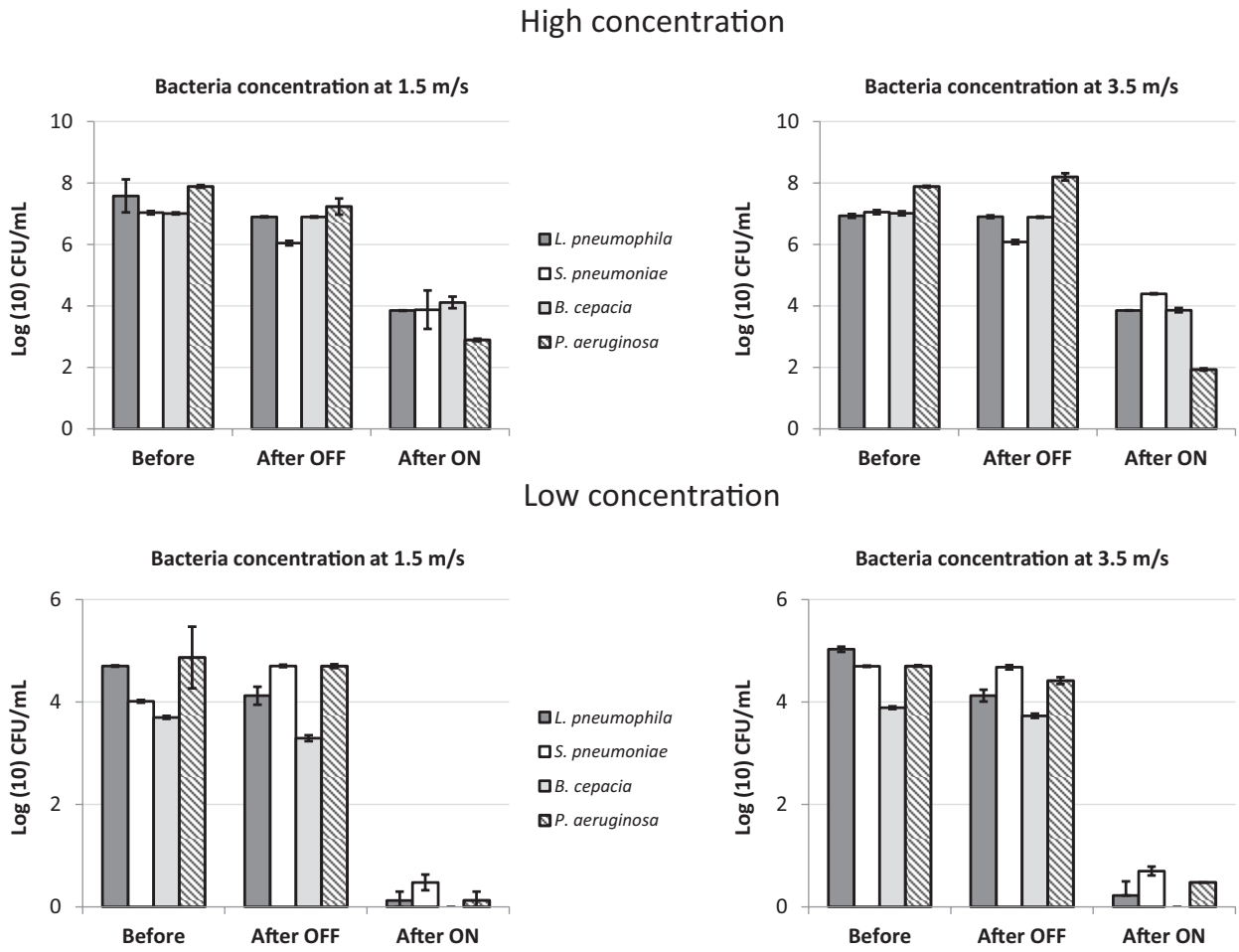

Figure 5. Bacteria concentration before and after exposure to the XP02 reactor. The experiments were realized at two different speeds (1.5 and 3.5 m/s). We followed two different conditions, high concentrations of bacteria and low concentrations of bacteria. Results were analyzed before and after exposure to the reactor and expressed in CFU/mL. The «After OFF» histograms represent the bacteria concentration after the reactor while it was turned OFF.

chemical compounds are mineralized by the action of the photocatalysis reaction to produce water and carbon dioxide.

The tests with the XP01 reactor gave us a starting point that we used to improve the efficiency of the system before testing a representative mixture of pollutants of an aircraft cabin. Results of the first test at 1000 ppbv/pollutant showed a total disappearance of each VOC within 10 h, without detection of any molecular intermediate. When a lower concentration was used, results were

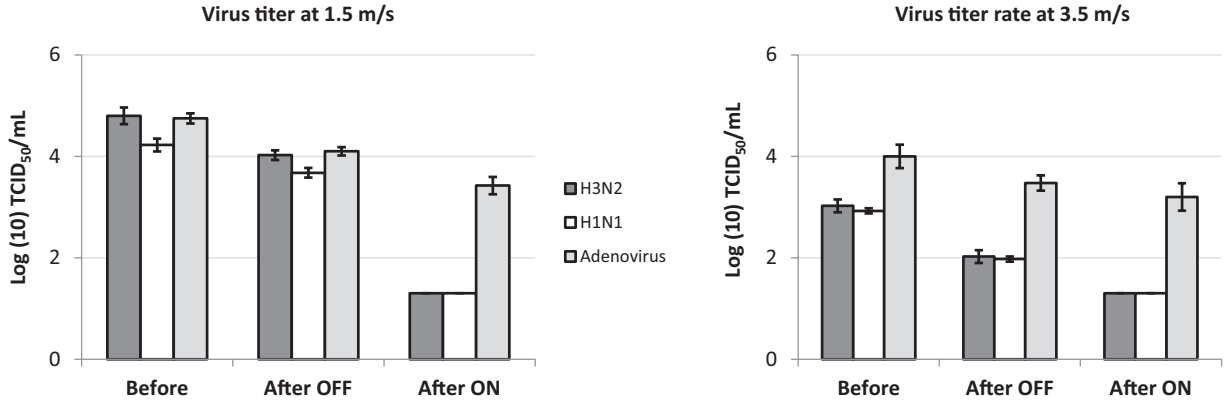

Figure 6. Virus titer before and after exposure to XP01 reactor.

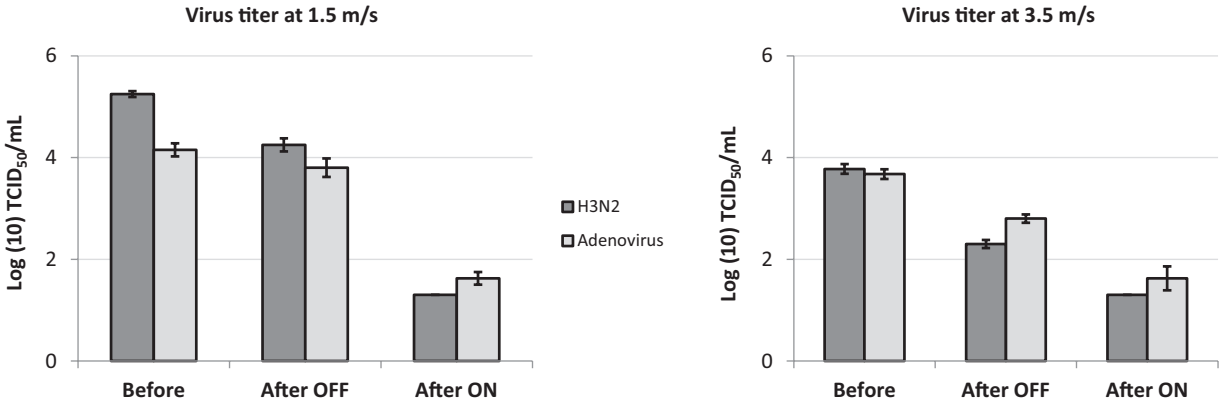

Figure 7. Virus titer before and after exposure to the XP02 reactor.

similar. These first two tests show that no by-product was generated and that the system totally mineralizes the selected VOC.

The efficiency of the system was improved in the XP02 reactor by increasing the irradiance of the lamp and modifying the composition of the photocatalytic coating.

The results show that the degradation rate is multiplied by two, at least, for VOCs (acetone, *n*-heptane and toluene in Tab. 2) except acetaldehyde. Since the pool of pollutants was not exactly the same between each test (replacement of formaldehyde by *o*-xylene), no assumption can be made about this specific behavior.

The test with the XP02 reactor, on a VOC mixture made of formaldehyde, dichloromethane, acetaldehyde, acrolein, acetone, 2-butanone, benzene, and toluene at 200 ppbv/pollutant showed a very low degradation rate for dichloromethane and a low degradation rate for acetaldehyde, acetone, and toluene. The sum of the concentrations of each compound was lower than in the test at 1000 ppbv/pollutant. Thus, the competitiveness between all the compounds cannot explain the lower efficiency. The main reason could be the presence of dichloromethane in the pool of pollutant. Competing with other pollutants, the very slow degradation rate of dichloromethane tends to lower the average degradation of other pollutants.

The results of the test at 200 ppbv/pollutant with the XP02 reactor are quite encouraging and show that ozone, aldehyde, ketone, and aromatic chemical families are degraded by the Aelorve technology. These results also highlight the quick degradation of ozone compared to its natural degradation.

Although the concentration of the VOC tested in laboratory is higher than the concentration of the VOC measured in aircraft cabins (Tab. 1), we can assume that the photocatalytic technology will be at least as efficient with low concentration as it is with high concentration. This hypothesis will be tested in further *in situ* tests.

In a typical cabin air ventilation system, 50% of the air supplied in the cabin comes from recirculated and filtered air. HEPA filters are used in aircraft in order to remove and minimize airborne contamination [34, 35]. Filters cannot remain as effective as they were at the beginning of their service life and require periodic replacement [36]. Furthermore, these filters are useless in order to reduce VOCs concentration inside aircraft cabins [11] and some studies highlighted that used filters, which are supposed to remove particles from the passing air, may pollute the air instead of cleaning it [37, 38]. Filtration can achieve a reduction of biological airborne contaminants but not to their complete destruction. Moreover, very small virus size makes their capture difficult [6].

Some evidence pointed out about the suitability of aircraft cabins in the spread of pathogens carried by passengers and crews members [5]. A recent review [5] reported cases of airborne infection such as tuberculosis, severe acute respiratory syndrome (SARS) and Influenza, spread among passengers inside aircraft cabins from several respiratory outbreaks [33].

In aircraft cabin, occupants have about 1–2 m^3 of available airspace per person [39]. This means that the air breathed by any passenger or crew member passes easily from anyone to his neighbor [40]. Efficient air suction and purification before recycling is the only chance to intercept pollutants and avoid repeated exposure of all people to infecting agents. This study shows for the first time a comparative study on both viruses and bacteria, which are involved in aerosol contamination. The XP01 reactor was able to efficiently eliminate Influenza viruses (H1N1 and H3N2), *L. pneumophila* and *B. cepacia* from the air in a single passage (3–4 log). Tests conducted with the XP01 reactor highlighted some resistance of *S. pneumonia*, *P. aeruginosa* (1 and 2 log, respectively) and adenovirus (0.8–1.3 log). This might be explained by the membrane physico-chemical properties of these bacteria and the organization of the viral nucleocapsid conferring an increase resistance against environment.

The XP02 reactor, which possesses a more powerful UV lamp than the XP01 reactor, was more efficient to clear adenovirus (1.5–2.5 log) and also bacteria. The results show that all bacteria strains were highly sensitive (3–5 log) to the system.

These values demonstrate that the XP02 reactor is actually more efficient than the XP01 reactor on both viruses and bacteria. At 10^6 CFU (which is by far higher than bacteria found in cough-generated aerosols (10^3 CFU) [41]), all bacteria strains were cleared (Fig. 5). Taken together, these results demonstrate that the XP02 reactor is also capable of clearing bacteria from contaminated air at a concentration of 10^6 CFU/mL, while providing a 2–4 logarithms reduction of virus concentration in the air processed through the reactor.

This study includes intrinsic efficiency tests of two experimental photocatalytic devices against VOCs of particular interest in an aircraft cabin environment and microbiological aerosols. Further investigations might be performed in a field or a real environment study in order to subsequently verify performances of such devices after their adaptation to the contingencies of an aircraft cabin environment (airflow, pollutant concentrations, air recycling, etc.). A similar approach was adopted for the use of an air decontamination

unit in a hospital. This study highlighted the efficiency of the system in both intrinsic and field tests, and supported the use of such supplemental air treatment measures [42]. Here we show that the Aelorve system is potent in combating VOCs and micro-organisms and therefore has a lot more advantages than the use of HEPA filters only, notably in strongly reducing VOC concentration in indoor environments and reducing the pressure loss of the air treatment system.

The SAVAB project has been designed to increase people welfare in aircraft cabins. The future of this system is to be extended to other confinements such as hospitals, trains, cars, BSL2 and BSL3 laboratories, museums and archives. Due to its proven efficiency in degrading a large panel of VOCs without emission of by-products, the Aelorve system is set to be an effective solution for improving health and comfort in several enclosed spaces (offices, dwellings, transports, etc.) by reduction of VOCs for which the long-term impact remains disregarded despite health concerns. Because of its high efficiency in eliminating micro-organisms, the Aelorve system would be of a great help in hospital by preventing the spreading of nosocomial diseases. Finally, cleaning precious environments such as archives, libraries or museums from damages linked to micro-organisms and VOCs would help to better conserve our heritage.

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