UVC-Mirror for effective pathogens inactivation in air ducts

Laura Treccani[1], *Daniele* Rovetta[1], *Gabriele* Zanetti[1], *Emanuela* Gobbi[2] – *Massimo* Turina[3] – *Matteo* Lombini[4] – *Fausto* Cortecchia[4] – *Emiliano* Diolaiti[4] – *Giuseppe* Malaguti[4] – *Andrea* Bianco[5] – *Giovanni* Pareschi[5] – *Giuseppe* Mongelluzzo[6] – *Luigi* Lessio[7]

[1]CSMT Innovative Contamination Hub, Via Branze, 45, 25123, Brescia Italy
[2]Università di Brescia, Viale Europa 11, 25121 Brescia Italy
[3]Istituto per la Protezione Sostenibile delle Piante (IPSP), CNR, Strada delle Cacce 73, 10135, Torino, Italy
[4]INAF - Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Via Piero Gobetti, 93/3, 40129 Bologna BO, Italy
[5]INAF - Osservatorio Astronomico di Brera, Via Brera, 28, 20121 Milano MI, Italy
[6]INAF - Osservatorio Astronomico di Capodimonte, Salita Moiariello, 16, 80131 Napoli NA, Italy
[7]INAF- Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio, 5, 35122 Padova PD, Italy

Abstract. Improving the air quality of indoor environments (IAQ) is of utmost importance to safeguard public health as people spend about 80–90% of their time indoor. Efficient Ultraviolet germicidal irradiation (UVGI) system represents a strategic and sustainable solution to protect from recurrent and new airborne pathogens. Here, we present a new approach to design highly efficient UVGI systems, which can be installed in existing Air Treatment Units (ATU) plants with minimal effort. The increased efficiency relies on the concept of an optical cavity, thanks to its shape and source position. The internal volume consists of a highly reflective cavity illuminated with UV-C lamps. Optical simulations permitted the variation of the parameters to maximize the internal irradiance and, thus, the performance. The sanitation efficacy of the system was assessed on a full-scale pilot system. Tests were carried out under normal operating conditions against various microorganisms showed an inactivation rate of > 99%. The benefits of such systems are triple and encompass economic, environmental, and societal aspects. Since the system requires little energy to operate, its application for air disinfection may yield significant energy savings and ensure a balance between energy sustainability and good IAQ.

1 Introduction

Air pollution is considered one of the primary threats to human health and well-being. Most of the global population (over 99%) inhales polluted air exceeding the World Health Organization's (WHO) recommended limits, which causes annually about 3.4 million premature deaths in built environments [1]. Indoor pollution levels are typically 2 to 5 times higher than outdoor pollution levels, as reported by the United States Environmental Protection Agency (US-EPA, https://www.epa.gov/). Biological pollutants, e.g. human

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pathogens, are critical in Indoor Air Quality (IAQ). The indoor air microbiome, composed of bacteria, fungi, viruses, and their metabolites, represents approximately 34% of the contamination present in the air [1]. Biological contaminants can originate from different sources (people, animals, plants, building materials) and are present everywhere, e.g., in office buildings, schools, universities, libraries, and households [2], [3], [4], even in a highly controlled environment like operating theatres and clean rooms [5], [6], [7].

Buildings and indoor spaces represent highly favourable habitats for microorganism growth and diffusion that can directly or indirectly affect the health and well-being of the occupants [5]. Release, circulation, and dispersion of harmful or potentially harmful biological agents within confined indoor spaces are considered a severe threat to public health. Therefore, there is a continuous effort to prevent or control their release [8]. Most people work in densely populated environments, increasing their exposure to many pathogens [9]. It is estimated that people spend most of their time (on average 85-90% or more) in indoor areas, e.g., houses, schools, university rooms, colonial buildings like shops, cars, planes, and workplaces [10], [11]. Prolonged exposure to pathogens and their metabolites significantly increases the health risk, which may lead to severe problems. Exposure to microbial aerosols may lead to infectious diseases, including nosocomial or associated infections, allergies, chronic pulmonary obstructiveness, cardiovascular diseases, cancer, and death, particularly in immunosuppressed individuals [12], [13], [14]. Therefore, the concentration and dispersal of airborne pathogens might become one of the main public health problems in building environments in modern life with an inadequate IAQ standard.

The importance of biological pollutants and their relation to IAQ is not new. Airborne transmission of pathogens to humans through the airborne route has long been recognized as a critical factor in several diseases and harmful infections [15], [16]. The recent SARS-CoV-2 (COVID-19) has drawn much attention to this issue due to its devastating health, social, and economic impacts worldwide. Before the COVID-19 pandemic, several studies showed the relationship between airborne transmission and indoor ventilation [17]. The emergence of Severe Acute Respiratory Syndrome (SARS) outbreak in 2002–03, the H1N1 influenza epidemic in 2011 and the threat of a different influenza pandemic, the Middle East Respiratory Syndrome (MERS) outbreak in 2012, the global prevalence of tuberculosis serve as timely reminders of the substantial risk posed to human health by airborne infectious diseases [17], [18], [19]. In the past, cases of legionellosis in different settings have been documented. Legionellosis is caused by Legionella, a genus of pathogenic Gram-negative bacteria, and is transmitted via inhalation of this pathogen in aerosol form [20], [21]. Estimates of legionellosis incidence in the United States range from 8,000 to 50,000 cases/year, although reported case rates vary significantly by region [20]. In 2022, the incidence of legionellosis in Italy was 51.9 cases/1,000,000 inhabitants, with an increase compared to the previous year (46.0/1,000,000) and a return to pre-pandemic incidence values [21].

Besides the higher awareness of the importance of airborne diseases, the recent pandemic underscored the critical importance of mitigating airborne transmission. In indoor spaces, there are many potential sites for spreading pathogens, including sick/infected persons, contaminated indoor air, and the threat of recirculated contaminated air through the heating, ventilation, and air conditioning (HVAC) systems. Different studies indicate HVAC, fans, humidifiers, etc., as the major sources of propagation and spread of microorganisms in indoor buildings [5], [11], [17], [22].

Transmission of bronchial asthma, influenza, and tuberculosis or viruses has been associated with HVAC systems [23], [24], [25]. Elevated concentrations of bacteria and fungi, which can diffuse through air movements, are found within HVAC systems [16], [26]. Insufficient ventilation or condensation in HVAC systems can create a favourable environment for the growth and dispersion of harmful bacteria through the ventilation ducts

[27]. Biological pollutants can deposit and grow on heat exchangers, in ducts, air handler units, and splitter boxes and can spread or release harmful or odorous byproducts throughout a building [28]. Significant proliferation of microorganisms occurs during periods of non-use of the HVAC system or when ventilation stops, and airborne pathogens might disseminate upon the restart of the system [29], [30].

Different approaches have been proposed to improve the general environmental microbiological air quality or IAQ. According to the inactivation mechanism, strategies rely on physicochemical and biochemical technologies [16]. Ultraviolet germicidal irradiation (UVGI) is an established means of disinfection and can be used to prevent the spread of infectious diseases. The UVGI triggers the pathogen inactivation when the UVC photons, between 220 and 280 nm in wavelength, are absorbed by DNA/RNA [31]. There is a long history of UV-C radiation as disinfection means. If appropriately used, UVGI can be safe and highly effective in air disinfection, thereby preventing the transmission of various airborne infections [32]. The use of UVC radiation for air treatment began already in the 1920s. By the 1930s, UVGI was efficiently used to sterilize the air in surgical operating rooms and school ventilation systems, significantly reducing the occurrence of measles [33]. In recent years, UVGI has received renewed interest after decades of underutilization and neglect [32]. The efficacy of UVGI systems is known to be affected by different parameters such as microorganism susceptibility, environmental factors, duct surface reflectance, etc. Different pathogens require a different UV-C irradiation dose for successful inactivation [34], [35], black surface than in clean ducts [36]. The disinfection efficacy of in-duct UV-C lamps can be increased by 20% with a reflective duct wall compared to under non-reflection conditions [37].

After the spread of the SARS-Cov-2 pandemic, the Italian National Institute for Astrophysics (INAF) has undertaken specific research and development activities [38]. Part of the work was devoted to making optical and computational fluid-dynamic simulations to optimize UVGI device performance. To overcome the current limits of UVGI systems and increase the pathogen inactivation performance, we present the UV-C Mirror, an innovative approach to designing highly efficient UVGI systems for sanitizing air described in a filed patent by the author [39]. The new UVGI system can be installed in different settings of existing HVAC and UTA systems. The main innovation consists of a highly reflective cavity that substitutes a section of the building's recirculating air duct. UVC lamps strategically illuminate this cavity. Carefully positioning the light sources and designing the cavity shape has been carried out to maximize UVC irradiance and, thus, the germicidal dose delivered inside the cavity. Ray-tracing software has been used for optical design, efficiency calculations, and light source position, while Computational Fluid Dynamics (CFD) has estimated the aerosol trajectories. This approach has permitted the simulation of various system parameters and the optimization of the inactivation performance. The proposed system was specifically developed to be installed in the Air Treatment Unit (ATU) plant at the Centro Servizi Multisettoriale Tecnologico (CSMT) in Brescia, Italy. This first prototype was constructed and installed in the ATU of CSMT to test the disinfection efficiency with different pathogens and operating conditions. Tests carried out with the prototype installed in an actual ventilation duct may provide reliable data about the applicability and suitability of the system in other settings where various environmental conditions (e.g., high airflow rates and varying temperatures) are commonly involved.

2 System design

The UV-C Mirror prototype was designed to be integrated into the existing ATU duct at CSMT headquarters. In particular, the system had to replace a portion of the duct with a section of 500 mm x 450 mm. The maximum available length was 1500 mm. Some space

around the duct was available and occupied by the prototype rounded profile on three sides with a curvature radius of 1500 mm, as shown in the exploded 3D image in Fig. 1. The internal surfaces are covered with Alanod, a highly UVC reflective material (Alanod GmbH & Co. KG, 2020). Five discharge low-pressure mercury (Hg) lamps with a power of 17 W at 254 nm wavelength are placed inside parabolic reflectors along the bottom plane. The lamps are sealed with UV-graded glasses with 90% transmissivity at 254 nm for safety reasons. The geometry of the prototype has been determined through simulations and in-depth analyses, which considered different shapes and source positions and aimed to determine the efficiency gain versus the constructive complexity. The approach used for the design and the simulations is described in detail in a previous work [39]. One of the main drivers for the optical design phase was the delivered irradiance or fluence rate (FR) (measured in mW/cm^2). The optical cavity concept was used to increase the FR inside the filter. The high reflectivity R of the internal side of the prototype permits rays to be reflected many times before losing power due to absorption (*Fig.* 2), and the cavity-rounded profile minimizes light leaks outside the reflective section. A closed cavity's power magnification or enhancing factor can be calculated from the material reflectivity R and has an exponential power law, as reported in a previous study [40].

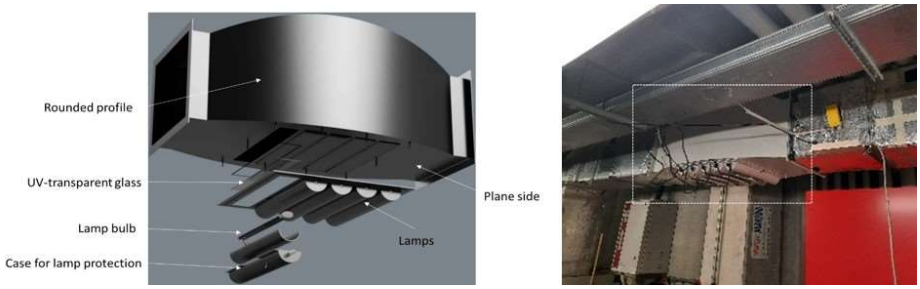

Fig. 1. Left: exploded 3D image of the system designed for installation in the existing ATU duct at CSMT Headquarters and adapted from (Lombini et al., 2022). Right: Prototype installed at CSMT Headquarters.

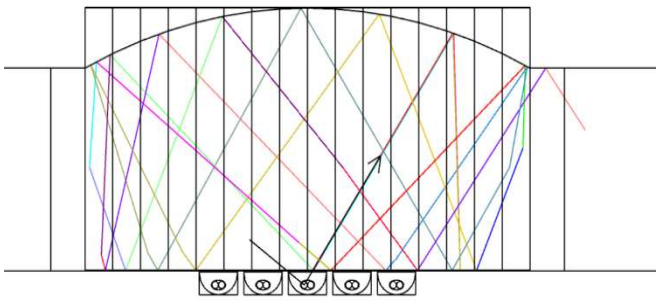

Fig. 2. Illustrative image showing the path of a single ray launched by the central lamp. The ray paths after every reflection are coloured differently. Some rays' power is absorbed when hitting the internal surfaces, and it either gets absorbed or exits the cavity volume.

Simulations also showed that the FR inside the system proposed is 2.5 higher compared to a system with a simpler configuration (same section of the outer duct, no rounded surface, and cylindrical light source inside the system volume). Meanwhile, CFD simulations would estimate the particles' trajectory and velocity inside the cavity. The local FR along the trajectories was multiplied by the local residence time t, the inverse of the velocity, to obtain

the delivered Fluence or Dose (in mW/cm^2), to the pathogens during the pass inside the cavity. *Fig.* **3** shows a graphic representation of droplet trajectory and velocity inside the filter for one of the cases studied, which aimed at simulating the tests performed with various pathogens at the CSMT facility. Six different test cases were simulated, reproducing the flow conditions of the experimental tests both in terms of air temperature (between 20°C and 33°C in the tests), and air exit velocity from the filter (varying from 2.75 to 4.25 m/s in tested cases). To this purpose, the entire ATU system was simulated by the commercial CFD code Ansys Fluent ®, imposing velocity inlet boundary conditions to its inlet sections to achieve, in the UVGI system, the exit velocity measured during experimental tests. At the outlet section of the UVGI system, a *pressure outlet* boundary condition was set. Droplets were simulated in the 0.5-25 μm diameter range, as this is the expected range for average droplet size emitted by humans during respiration [41], [42]. Simulations consider ~ 3000 simulated droplets per run. The air flow was simulated as turbulent, using the realizable k-ε model, with a second order upwind spatial discretization scheme for momentum and energy equations. As a result of simulations, a prediction of the trajectories of droplets was obtained. The ability to predict position and residence time inside the filter of droplets allow a detailed simulation of the fluence rate to which each simulated droplet is exposed.

For the simulated case, the equivalent fluence (Feq) corresponds to Feq > 14 mJ/cm^2, which is adequate to inactivate some pathogens like SARS-Cov 2 requiring about 3-4 mJ/cm^2 to achieve at least a log2 inactivation rate [43].

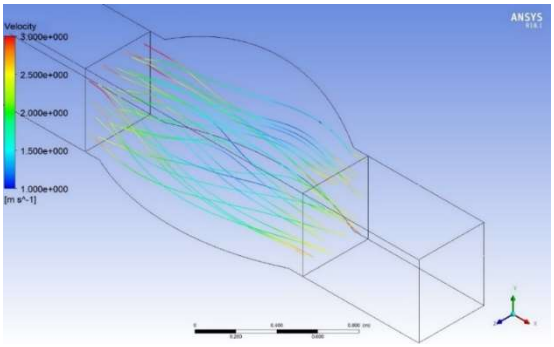

Fig. 3. Graphic representation of velocity and trajectory of simulated droplets moving inside the filter for an example case study.

3 Assessment of UV-C mirror sanitation efficiency

The assessment of the performance of the innovative system was carried out under normal ATU working conditions and according to a self-developed protocol, which follows the main guidelines provided by the standard ISO 15714:2019. Sanitation efficacy was assessed using two model pathogens representative of airborne pathogens, namely a bacterium (*Bacillus atrophaeus*) and a virus (Tobacco Mosaic Virus, TMV). The experimental setup mainly consists of a liquid nebulizer for aerosol generation and dispersion of the microorganism inside the duct and a system for microorganism sampling and collection. The inactivation rate was assessed by one-pass exposure system without recirculation. To determine the effect of the UVC light test, the experiment was repeated at different conditions by switching the UVC lamps on and off. Tests with UVC light off were used as control. For each microorganism, three independent tests were carried out on different days. In each test, air samples were collected three times. The airflow rate and environmental parameters, such as temperature and RH, were constantly monitored during the tests. A liquid nebulizer for

suspensions was used to generate an aerosol of the test microorganisms upstream of the system. Highly concentrated microorganism dispersions were used. The nebulization was maintained for 30 min, corresponding to a single test's duration. The air was sampled downstream of the system using a biological air sampler (Coriolis micro, Bertin Technologies). The sampler relies on a liquid cyclonic technology, enabling the collection and concentration of microorganisms in a sterile liquid ready to be analysed with microbiological and molecular biology methods.

After the air sampling, the bacteria were plated and grown on agar plates at controlled conditions till bacteria colonies became visible and countable. Counting the number of viable bacteria by forming visible colonies on agar plates, known as colony formation, is a standard method for determining bacterial viability. Many colonies indicate increased viable bacteria and poor sanitation efficacy. On the contrary, few or no colonies indicate poor bacteria viability and a high sanitation efficacy.

To test TMV's viability, a specific biological assay was applied using tobacco plants [44], [45]. Active and living TMV induce visible local necrotic lesions on the plant leaves. Tobacco leaves were inoculated with solutions corresponding to different air samples and observed until necrotic lesions became visible. The number of necrotic lesions is proportional to the number of active viruses. A high number of lesions indicates increased viable viruses and poor sanitation efficacy. On the contrary, few or no lesions indicate poor or no virus vitality and, therefore, a high sanitation efficacy.

The air disinfection efficacy was determined as inactivation rate (%IR) determined as follows

$$\%IR = \frac{N_{UVC-OFF} - N_{UVC-ON}}{N_{UVC-OFF}} x100$$

Where

N_{UVC-ON}: number of viable microorganisms (bacteria or viruses) sampled downstream of the sanification system (UV-C mirror) with the UV-C lamps switched ON;

$N_{UVC-OFF}$: the number of viable microorganisms (bacteria or viruses) sampled downstream of the sanification system (UV-C mirror) with the UV-C lamps switched OFF.

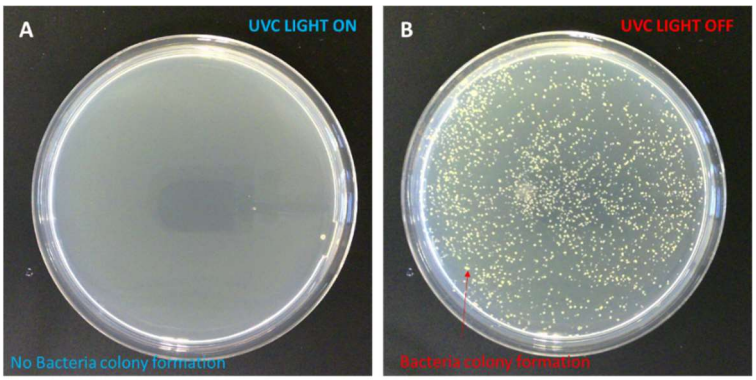

Fig. 4. Representative images of agar plates with bacteria collected from the air samples. Air samples were collected from the ATU, where the innovative sanitation system UV-C Mirror was installed. A: UVC-lamps ON. B: UVC lamp OFF used as control. With the UVC lamp on, no bacteria colonies formed, indicating the absence of viable bacteria, thus ensuring the system's high sanitation efficiency. On the contrary, when UVC lamps were switched off, an increased number of bacteria colonies were found. Bacteria colonies appear as yellowish, roundish spots as representatively indicated by the arrow. A high number of bacterial colonies indicates the presence of a high number of viable bacteria.

Results showed that the system proposed can efficiently inactivate microorganisms with a one-pass exposure system (without recirculation). The inactivation rate for bacteria is very high and in the range of 99-99.99%, corresponding to about 3-4 $\log_{10}$ reduction. The sanitation efficacy of the innovative system proposed can be better appreciated by looking at some exemplary images of agar plates where bacteria collected from air samples were cultivated (Fig. **4**). No bacteria or very few colonies were visible on agar plates when UVC lamps were switched on (Fig. **4**A), indicating that bacteria were inactivated by passing through the innovative UVGI system. On the contrary, many colonies, thus a high number of viable bacteria, were detected when UVC lamps were switched off (Fig. **4**B). The results are auspicious, considering that the inactivation occurs after only one-pass exposure, which is very rapid. The air velocity measured in the duct is relatively high at about 4-5 m/s. Considering the measured airflow, the total time for a microorganism to traverse the system is estimated to be about < 1 s. The inactivation percentages for the TMV ranged from 70 to 90%. The results clearly demonstrated that the proposed system is effective against a relatively robust and UVC-resistant virus-like TMV. Inactivation of TMV with ultraviolet treatment typically requires an extended processing time and much energy [46].

4 Discussion

Air sanitation in indoor, crowded environments, such as in public buildings, offices, schools, health structures, etc., is paramount to provide healthy and safe conditions to occupants and workers. In this study, a new air sanitation device, consisting of an optical cavity with an inner UVC highly reflective surface and UVC sources, was designed to be installed in a UTA HVAC system and tested for its efficiency at microorganism inactivation. The results showed a high sanitation efficacy as the viable bacteria and viruses could be reduced up to 99.99% and 90%, respectively. Tests highlighted the optimal inactivation efficiency for bacteria at all the airflow rates tested (up to 5 m/s). At first sight, a minor effect of the virus was instead noticed. The main difference may rely on the different UV-C susceptibility of the microorganism, which strongly depends on other different factors, such as the ability of different microorganisms to recover UV radiation-induced damage, the UV dose, fluence rate, temperature, RH, exposure time, and the particulate/moisture present in the air [34], [35], [39], [47].

The chosen microorganisms have different UV-C susceptibility levels, which may be influenced by the environmental parameters (e.g., RH), media, or support. For example, the inactivation dose D90 for achieving 90% inactivation reported for *B. atrophaeus* varies greatly. The inactivation rate for spores in the air is between 2.7-9.4 mJ/cm^2 (Kesavan et al., 2014) or 14.4 mJ/cm^2 at low RH (https://uv-light.co.uk/uv-dosage-required-to-kill-microorganisms). A direct comparison between these studies may be inappropriate due to the varying experimental conditions used to estimate the inactivation rate. Similarly, no clear pattern indicates different sensitivities to UV light across different types of ssRNA viruses. However, a study found that single-stranded viruses (ssRNA and ssDNA) were more susceptible than double-stranded viruses (dsRNA and dsDNA) [48] for TMV, different inactivation dates are reported. Infectious nucleic acid from TMV is inactivated by UV light (2537 A) with a minimum quantum yield of $3x10^{-4}$ [49]. However, the source of UV radiation must affect the virus infectivity [50]. For SARS-Cov 2, it is reported that about 3-4 mJ/cm^2 is sufficient to produce at least a D90 inactivation rate (99%) [43]. Besides the microorganism susceptibility, the performance of an in-duct sanitation device can be affected by flow rate and microclimatic parameters. Further investigations are ongoing to determine their effect on the inactivation efficacy in our prototype.

One significant advantage of UV-C Mirror lies in its simplicity. It does not contain any components susceptible to microorganism colonization. Some components of the HVAC

systems, e.g., filters, can be quickly colonized by different microorganisms, which can be further released indoors, becoming a potential risk for contamination and spreading [29], [30]. Significant microorganism growth can occur during ventilation stoppage or non-use, and airborne pathogens may spread when the HVAC is switched on. Our systems can reduce the risk of spreading after stoppage. E.g., the lamps can be switched on before air circulation, and the inner surface can be sanified to inactivate microorganisms that eventually grow on the inner surface. The absence of parts vulnerable to bacterial growth ensures a higher level of safety and minimizes the risk of contamination within the system. Consequently, it contributes to maintaining a clean and safe environment, which is crucial in various applications, particularly in fields such as healthcare, food processing, or any setting where preventing contamination is paramount. This simplicity enhances the system's reliability, facilitates easier maintenance, and reduces the need for frequent cleaning or sterilization, thus optimizing operational efficiency and overall performance.

A reflective inner surface can enhance the disinfection efficacy [29], [36], [37]. In our systems, a higher effect is achieved as the reflecting surfaces and a proper design of the filter shape are combined. This enables the maximization of the internal energy density. Power density enhancement inside a volume due to a high reflectivity of the inner surfaces is exploited in different technological applications, such as integrating spheres [51] or Fabry-Perot interferometers [52]. Regarding the UVGI, the enhanced sanitization efficiency achieved with a UVC source placed within a reflective tube is reported by Jensen [53] and subsequent studies [36], [37], [54]. As no secondary effects result from light absorption by pathogens (or air), the entire UVC light dose can be applied in segments through multiple internal reflections. The concept of power density remains applicable to different air volumes, even large ones. This includes residential or industrial air ducts. Alanod was chosen to coat the internal surfaces of the cavity. It is a commercial UV high-reflective anodized aluminum provided in long sheets, thus convenient for the proposed use.

Besides preventing airborne disease transmission and other health risks, another advantage of the proposed system is its low environmental impact. The system is chemical-free and does not leave behind any residues. Any toxic or potentially harmful substances or byproducts dangerous to building occupants and the environment are released during operation. Compared to other systems, for instance, it can generate ozone emissions, which can be very harmful, causing headaches, throat dryness, asthma, and even life-threatening at high levels. UV-C Mirror is designed to allow people to be present during its use and operation.

UVC air disinfection is commonly promoted as an energy-efficient way of reducing infection risk compared to ventilation or filtration, two of the most conventional approaches to reducing pathogenic bioaerosols in indoor environments [55]. Ventilation is energy-intensive, as indoor and outdoor must be exchanged, and the intake air must be heated or cooled. Ventilation cannot be applicable or suitable for the whole year and depends on the outdoor air quality. Air filtration requires good filtration media with high Minimum Efficiency Reporting Values (MERVs), essential for high bioaerosol removal performance. High-efficiency particulate air (HEPA) filters can be highly effective (e.g., 99.97 % collection efficiency for 300 nm particles), but the low porosity (<30 %) increases the flow resistance, which results in high energy consumption. Additionally, filters require frequent maintenance and replacement to avoid the proliferation of pathogens on their surfaces. This further increases the system's operating and equipment costs [56]. UVGI is considered an affordable and ready-to-apply strategy to control airborne pathogens compared to ventilation and filtration. Our system requires minimal maintenance, mainly replacing the lamps after 8000-10000 hours, roughly once a year if the lights are always on. Cleaning of UVC lamps is not required during regular operation. To protect the light bulbs from dirt and accidental breakage, the lamps are sealed by UV-transparent glass. This can further prevent UV-C light

output reduction and increase the usage time and effectiveness. The inner surfaces of the system are designed to be easily cleaned with standard cleaning procedures, e.g., during ATU routine maintenance. As the system does not contain any filters, there are no issues with flow resistance and increased energy consumption.

The main features of the UVC-Mirror are briefly summarized in Table 1.

Table 1. Main features of the UVC-Mirror.

Main Features	
Main disinfection principle	UV-C irradiation / Active inactivation of pathogens
Installation in existing HVAC	Possible
Pressure drops in HVAC	None
Maintenance	Only substitution of UV-C lamps after 8000-1000 hours (about once a year)*
Energy consumption	2400 kWh/year (if 24h/day on)

**besides regular maintenance of the HVAC according to in-force regulations.*

The energy consumption of our UVC system is limited to the energy that the lamps use when turned on, which is approximately 2400 kWh/year if the system is functioning 24h/day. Currently, the system is equipped with mercury UVC lamps as they have sufficiently high emission power and have affordable costs. We envisage substituting conventional mercury UVC lamps with more environmentally friendly UVC sources, such as UVC Light Emitting Diodes (LED). Substituting conventional UVC lamps with energy-saving LED UV-C lamps will further decrease overall energy consumption and have a lower environmental impact. However, this solution is still poorly affordable as LED UVC lamps are more expensive than conventional UVC mercury lamps. Substituting mercury UVC lamps will further improve human and environmental health [57].

5 Conclusions

People spend a significant amount of time indoors in air-conditioned spaces. The impact of health-related issues linked to poor indoor air quality and the risks of infection due to new or recurrent pathogens affect millions of people and are very high costs for society. UV-C mirror represents a sustainable approach for air disinfection of modern buildings, where safety for occupants and energy savings must be guaranteed. The innovation is the quantitative and accurate analysis of the performance of a device that exploits the concept of enhancing the fluence rate produced by multiple light reflections inside an optical cavity. Microbiological tests confirmed the performance estimation based on ray-racing and CFD analyses in actual conditions and a real-scale prototype. The disinfection performance of the UV-C Mirror is high, as bacterial and viruses can be inactivated up to 99.9%, even in single-pass disinfection and at ultrashort disinfection time (< 1 s) for at high airflow rates. Further, UV-C mirror is a low-maintenance, low-energy consumption system. It only requires periodic lamp replacement (once a year, assuming a 24h/day usage) and no other maintenance operations. The energy consumption is limited to the energy consumed by the lamps. In conclusion, the UV-C mirror represents a simple approach that can be implemented in various sustainable strategies to enhance IAQ and protect individuals against indoor airborne infectious agents.

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Symbology

Feq	Equivalent fluence, mJ/cm^2
FR	Fluence rate or irradiance, mW/cm^2
IR	Inactivation rate, %
Log inactivation/reduction	Logarithmic inactivation/reduction refers to a percentage that a given pathogen will be inactivated by a disinfection
R	Reflectivity

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