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UV-C Light, an Example of Application for Air Sanification

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Abstract. Within the activities for the fight against the pandemic caused by SARS-CoV-2, a lot of emphasis on air sanification was put. The most efficient technique is the use of ultra violet germicidal irradiation (UVGI) to inactivate airborne pathogens. The most utilized UVGI sources are mercury lamps. To enhance the UV irradiation and make it more effective different solutions are being analyzed, between these the study of UV reflective materials is having an important role. When the air passes in a duct the reflections increase the irradiation power, so the dose with which it is illuminated. Using these recent findings, INAF in collaboration with NVK Design have developed a stand alone UVGI air sanification system, Saturno, that uses 4 UV-C mercury lamps mounted in a UV reflective cavity. The air of the room is forced by two fans through the cavity and it is efficiently disinfected.

Key words. UV light, SARS-CoV-2, air disinfection, mercury lamp

1. Introduction

Since the beginning of 2020, the world has been overwhelmed by the Coronavirus Disease 2019 (COVID-19) pandemic (Nicola et al. 2020; Zhu et al. 2020). The virus, Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2), is very contagious and has affected over 300 million people in two years (Khan et al. 2021; Sohrabi et al. 2020). Since the pandemic's beginning, the scientific world has been working to find different approaches to contain and limit the diffusion of SARS-CoV-2. It should be noted that the pathogen that causes COVID-19 is airborne transmitted. The World Health

Organization (WHO) has identified two transporters for the virus, droplets with a diameter of $\geq 5 - 10\mu$m and aerosols with diameter $\leq 5\mu$m (Wilson et al. 2020; Cai et al. 2020; Jarvis 2020; Tang et al. 2020). In this respect, the virus can remain viable in aerosols for up to 3 hours (van Doremalen et al. 2020). Moreover, the particles responsible for carrying the pathogen can travel for nearly 8 m when sneezing and over 2 m when coughing (Bourouiba 2020; Loh et al. 2020; Jarvis 2020). These findings on the viable rate and the travelling distance of SARS-CoV-2 have brought to the restrictions that have had a significant impact on human lives worldwide in the last two years, in particular the necessity to wear a face mask and social distancing, at least 1 m between people, to limit the transmission of the virus. The very high contagious rate and the difficulties in fighting a new pathogen have brought to the study and consideration of different methods to contain the airborne virus. In particular, air sanification approaches based on the use of Ultra Violet Germicidal Irradiation (UVGI) are of large interest. Kowalski (2010); Coohill & Sagripanti (2008); Sabino et al. (2020). The UVGI technique uses UV-C light at wavelengths between 220 and 280 nm to irradiate different pathogens. The DNA/RNA of viruses and bacteria absorb UV-C light and inactivation paths can occur with different probabilities according to the kind of microorganism. (Kowalski & Bahnfleth 2000; Kowalski 2010; Green & Scarpino 2001; Beck et al. 2016; Cadet et al. 2005; Reed 2010; Kowalski 2010; Lee et al. 2011; Kim & Kang 2018; Gerchman et al. 2020a).

The UV based disinfection is a consolidated technique; the studies of this method started at the end of the 19th century, when the British scientists observed the effect of sunlight on bacteria Downes and Blunt (Downes & Blunt 1877, 1879; CURSED 2011). In 1930, for the first time, the action spectrum of the bactericidal effect of artificial UV-C light was studied by the American scientist Frederick L. Gates, that studied the impact of ultraviolet light on *Staphylococcus Aureus* bacteria. Finding the action spectrum peak at about 265 nm (Gates 1930). The virucidal and bactericidal effect of UV light is dose-dependent (mJ/cm^2) and is directly proportional to irradiance (mW/cm^2) and exposure time (s) Biasin et al. (2022); Gerchman et al. (2020b). The survival fraction (S) is equal to the ratio between the alive population after (N) and before (N_0) irradiation, which is an exponential function of the dose (D), and k is a decay constant that depends on the microbe species (Kowalski 2010).

$$S = N/N_0 = e^{-kIt} = e^{-kD}$$

Several experiments using UV-C light and SARS-Cov 2 have been conducted. In this respect different studies have observed a 2log inactivation rate with doses around 3-4 mJ/cm^2 (Biasin et al. 2021; Kowalski et al. 2020; Inagaki et al. 2020). In the case of aerosols other factors influence the inactivation of pathogens, relative humidity and on the dust that can absorb part of the light (McDevitt et al. 2012; Tseng & Li 2005; Eisenlöffel et al. 2019).

Since the pandemic's beginning, in February 2020, the Italian Institute of Astrophysics (INAF) has begun a series of projects and research to help in the fight against COVID-19. There has been strong attention on sanification systems, and in this paper, the aim is to present the prototype of Saturno, a UVGI lamp.

2. UV Radiation and Artificial Sources

Ultraviolet light is divided into three bands: UV-A between 320 nm and 400 nm, UV-B between 280 nm and 320 nm, and UV-C between 100 and 280 nm. In outer space, the source of UV light is the sun, but not all the frequencies are transmitted to the Earth. The ozone layer absorbs 100% of the UV-C

radiation and 95% of the UV-B radiation (Diffey 2002). Therefore, it is not possible to use the sun as efficient light source of disinfection.
Fortunately, there are different artificial sources of UV light. The most used are mercury lamps that emit UV-C light at 253.7 nm wavelength and are composed by Mercury and a gas, typically Argon, in a tube where high voltage is applied (Ahmad et al. 2017). There are both low and medium/high-pressure lamps. The first type work at a pressure of 1 Pa and provide a flux of about 0.2-0.3 W/cm^2. They also emit radiation at 185 nm, which combined with oxygen forms ozone. In low pressure lamps the mercury is usually contained in fused quartz, that does not transmit the 185 nm frequency light (Schalk et al. 2006). Low pressure lamps have another subcategory, that is amalgam lamps, these do not have pure mercury but a mercury amalgam, the cost is low, their efficiency is about 30% and can last up to 10000 hours, the UV flux is in average 1 W/cm^2. Medium/high pressure lamps have a higher electrical voltage input resulting in a pressure of 100 kPa. The efficiency is lower than low pressure lamps, about 10-15% and they have a shorter lifetime, in average 5000 hours, but the UV flux is higher, up to 35 W/cm^2. The major problem with mercury and amalgam-based lamps is the pollution, their disposal is very harmful for the environment because of the presence of Mercury.
UV Light Emitting Diodes (LEDs) have been developed over the last 30 years. In 2014 the three Japanese inventors of UV LEDs: Isamu Akasaki, Hiroshi Amano and Shinji Nakamura won the Nobel Prize for this development (Akasaki 2015; Akasaki et al. 2014). UV LEDs compared to lamps have some significant advantages, they are: mercury-free, have higher energy efficiency, a longer lifetime, a more homogeneous irradiance both spatially and in time, no warm up time needed and the prices are getting lower since the request and the production is increasing, but the output power is still lower than mercury lamps (Chen et al. 2017; Heber 2014).

3. Reflective Materials to Enhance UV-C Disinfection

To enhance UV-C sanification lamps, other than increasing the power of the light and diminishing the irradiance distance, different types of coatings have been tested to intensify the reflectivity. When the UV light is reflected, it can still contribute to the disinfection with an increasing gain proportional to the number of reflections; in other words, the effective irradiance increases and the sanification power is augmented (Jensen 1964; Ryan et al. 2010).
The simplest approach for having reflective surfaces is the use of first surface mirrors. They do not have any transparent layer over the reflective surface; they work well, but their cost is very high and they have a low durability. In a paper published in 2018, to enhance the UV-C radiation reflectivity, sheets made in diamond-plate aluminum were used, reducing by 33% disinfection time, the major problem for this technique is the high cost(Lindsley et al. 2018). Among materials with high reflectivity, an aluminum-based coating has been developed by Alanod. Indeed, the Alanod MIRO UV-C coating has been specifically engineered for short wave ultra violet light and it is characterized by a long lifetime and has a spectral reflectivity of 90%.(ALANOD GmbH & Co. KG 2020).
To increase the irradiation, UV reflective paint has been studied. The American company, Lumacept, has developed a reflective coating for UV-C light, using nanoscale inorganic oxides, which reduce the UV absorption. Normal wall paint absorbs up to 97% of ultraviolet light, using this paint the reflectivity can reach 67%, but it has been implemented only for application on walls (Rutala et al. 2013, 2014; Jelden et al. 2017; Krishnamoorthy & Tande 2016).

4. Example of Stand-Alone System for Air Sanification: Saturno

In order to obtain an efficient disinfecting device, the combination of the UVGI disinfection lamps in a reflective cavity is a clever approach. In this context, Saturno is a project in collaboration with NVK Design of Natasha Calandrino Van Kleef, which took care of the design and the INAF. Because of its shape, the sanification lamp gets its name from the planet Saturn (fig1).

Fig. 1. Zoom in, on the top part of the system, the shape recalls the planet Saturn.

The project, which is still in a prototype phase, consists in the design and testing of a new lamp for room sanification, in particular it is thought for schools thanks to its simplicity and limited cost. In school, indeed, it is not always possible to change the air frequently for structural problems and to control the environmental pollution, in winter with the heating on and in the hotter season with air conditioning working the waste of energy is very high; therefore, UV-C lamp are a good solution to this problem (Srivastava et al. 2021).

The Saturno lamp has been designed to aspire the air into the top semi-sphere by two fans. The air flows inside the top half, where 4 UV-C mercury lamps irradiate

Fig. 2. Picture of the whole system, including the pole, the vase and the base with wheels.

the air. The inner top half semi-sphere of the lamp is highly reflective. The sanified air passes through the top of the lamp and back in the room where the lamp is located. The lamp is 2.40 m tall including the base, the diameter of the sphere is 700 mm, of the dish containing the fans

850 mm, the spherical part of the lamp is high 855 mm (fig 2). The top semi-sphere is covered on the bottom by a plate containing two fans that suck in the air. On top of the fans there are three round slabs, two have the same diameter that make the air's path inside the lamp longer and increases the dose with which it is irradiated and inactivates the pathogens contained; the air exits the structure from the top that has a funnel shape (fig 3). A 1 m diameter plate covers the bottom semi-sphere to stop the UV radiation from leaving the lamp and avoid the harmful effects of contact with people; inside its cavity, the cables and the transformers are stored. All the wires pass inside the pole, and the plug comes out underneath the lamp. The UV-C lamps used are 13 W Philips TUV PL-S mercury light bulbs. The fans used are RadiCal EC centrifugal modules, with a 10 V output.

The prototype of the lamp is in iron and aluminum, making it heavy and difficult to handle. The final product should be in polyethylene plastic, which is efficient in shielding the UV frequencies of light and the lamp will be more than 70% lighter.
On this prototype irradiance and air flux tests were conducted. The air purifier was assembled with three UV-C lamps, mounted horizontally with respect to the pole. Using a radiometer two measurements were taken, corresponding to the points of maximum and minimum flux, both without the lid on the lamp, the first test was conducted by placing the sensor parallel to the lamps, and pointing in between two of them, the irradiance is 1.03 mW/cm^2. The second measurement was taken with the radiometer placed perpendicular to the lamps, attached on the upper plate, pointing downwards and the irradiance is of 6.15 mW/cm^2. The air speed was measured using an anemometer, the speed of the air entering one fan at maximum velocity was 5.2 m/s, considering the use of two fans the air flux is 10.4 m/s and the speed exiting the funnel on top of the lamp was 1.7 m/s.

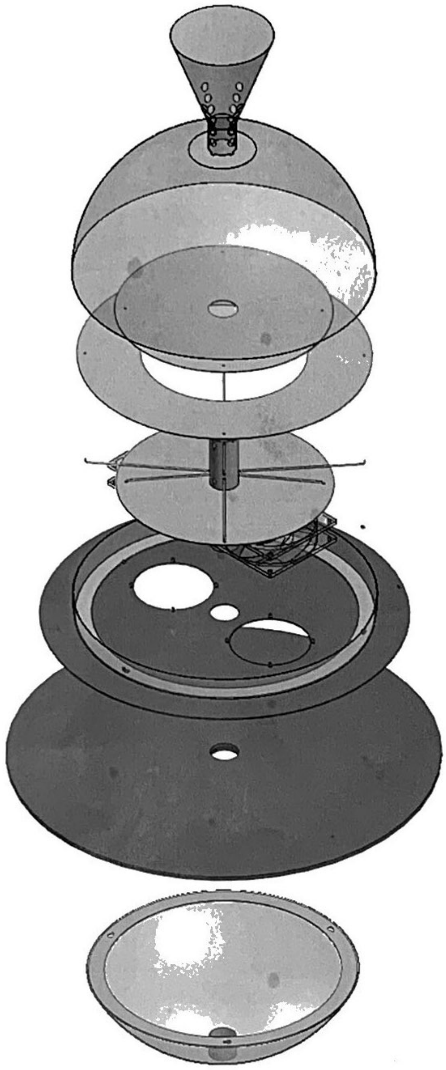

Fig. 3. Internal structure of the lamp. From the top there are: the fennel exit for the air, the top part of the sphere that contains the three plates and is closed by the slab with the holes for the fans, then the large plate that closes the lower part of the lamp.

Knowing the fan diameter (95 mm), it is possible to calculate the flow rate enter-

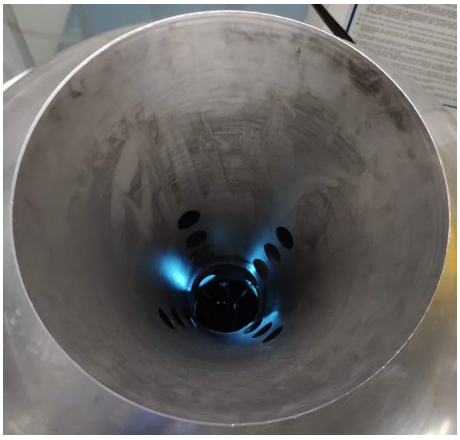

Fig. 4. Top view of the lamp while functioning, it is possible to note the blue visible light, but there is no UV radiation coming out.

ing and exiting the lamp. The flow rate entering the lamp for one fan is 0.08 m^3/s, considering two fans working at 90% of the maximum there is a flow of 0.13 m^3/s and the flow going out is 0.09 m^3/s. The 0.04 m^3/s flow difference is explained by a part of the air that does not complete the sanification cycle and filters through the sides. The radiation loss escaping from the sides and from the top were measured by means of the UV-C radiometer and it was zero. This is very important because UV-C light is harmful for the human being and the daily limit dose is small (fig 4). The fans employed in Saturno at maximum speed make some noise but it is not excessive; indeed, it is possible to have a conversation at a normal voice volume without problems, but more quantitative tests are required to have a precise evaluation.

5. Conclusions

The importance of air sanification has been highlighted by the SARS-COV-2 pandemic, in particular the UVGI systems are in continuous progress and have been recognized as very precious in the pandemic fight. The most recent innovations, in particular the development of UV-C LEDs could extend the use of this technique making it safer to use.

Among all the recent proposes for air sanification the collaboration between INAF and NVK Design has brought to the Saturno project that gave some interesting results, even though it is still in the prototype phase. The tests conducted on the lamp have given good results. The Saturno lamp, in one hour aspires 468 m^3, considering two fans and lets out 324 m^3 of air. The air that filters through the gaps on the sides, in 1 h would be 144 m^3, even though it does not complete the disinfection cycle, having high values of irradiance the sanification process is still effective.

The irradiance has been measured equal to 6.15 mW/cm^2, without considering the reflectivity of the inside of the sphere and with a UV source less than the final version, that means a dose of 6.15 mJ/cm^2 after 1 s. The doses to inactivate UV sensitive pathogens are easily achieved, quickly, also referring to the most recent SARS-CoV-2 the inactivation fluence is reached rapidly, around 4 mJ/cm^2 (Tang & Sillanpää 2015; Biasin et al. 2021; Kowalski et al. 2020; Inagaki et al. 2020; Beck et al. 2015).

The stand-alone system can be implemented and improved: using a plastic material for the structure will vastly reduce the weight, making it easy to set up and manoeuvre without losing the UV radiation shielding. The absence of UV radiation, while the system is in function is very important, the air sanification can be continuous, also with people present in the room.

Enhancing the coating of the inside of the sphere and of the surface of the plates contained inside it, with a highly reflective material, for example Alanod, increases the sanification power.

Adding one or two fans would surely accelerate the disinfection process, but the noise could become annoying, especially if the system is located in a working or studying place, a better solution would be to use

more than one lamp in the same room.
A comparison with a UVGI systems already on the market was brought on to understand the validity of the project. The mass flow rate is good, the most powerful application by Beghelli has a maximum of 200 m^3/h and a radiant power of 14 W, using two 24 W UV-C light bulbs (Beghelli s.p.a. 2021).The Beghelli system has a volume of 0.02 m^3 compared to 0.8 m^3 of Saturno, the weight is a lot smaller. Saturno uses 4 14 W UV-C lamps, for a total of 56 W against the 48 W of the Beghelli. The design of the applications are very different, but the values of air flow and irradiance measured are consistent and superior even though it is only a prototype.
Some ideas for the future development may comprehend a wireless control system and making it home automated.

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