Sanitizing of Confined Spaces Using Gaseous Ozone Produced by 4.0 Machines

Roberto Mosca, Marco Mosca, Roberto Revetria, Lucia Cassettari, Fabio Currò, Gabriele Galli

Abstract— **A fundamental aspect of the fight against the Coronavirus and against any other virus, is represented by the sanitization of the sites and objects contained therein. This operation is normally carried out using mixtures of ozone and steam and it is certainly effective but also limited due the damages that the vapor can cause to rooms and objects. The following paper introduce machines able to overcome this issue thanks to innovative systems based on the principles of Engineering 4.0. Those systems reproduce the Chapman cycle in the to-be sanitized environments which allows producing ozone in a gaseous state, in the proper quantity and for the time necessary for sanitization. At the end of the operation, the ozone will be converted back into oxygen, leaving the environment re-habitable by humans and pets in a short time. The operation has low costs and times and guarantees positive results. This is therefore a real revolution to be considered today against the COVID-19.**

Index Terms— **COVID-19, Industry 4.0, Ozone, Safety, Sanitizing**

I. Introduction

THE SARS-CoV-2/COVID-19 pandemic raises the bar for the effectiveness and improvement of disinfection, sanitation, and sterilization procedures not only in the health care facilities but also in work environments such as schools, labs, beauty centers, gyms, grocery stores, and many more.

During the lockdown phase due to the spread of COVID-19 in March 2020, an important problem emerged in the battle against viruses, namely the need to sanitize the environments, as well as the clothing and footwear worn by those who come from contaminated environments.

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The most common sanitizing method is the one that involves the use of ozone mixtures in water vapor carrier fluid which is proved to be an effective wet treatment but with non-trivial drawbacks such as the risk of damaging walls, floors, furniture curtains, and carpets. Therefore, such treatment requires careful drying and, sometimes, restoration and subsequent cleaning with not negligible costs. Another huge limitation is the impossibility of treating machines, electrical and electronic systems, ferrous surfaces, desks, paper, and books.

The attention of the Department of Mechanical Engineering (D.I.M.E.) of the University of Genoa and mcGEAR researchers has therefore turned to the possibility of conceptualizing and designing a non-invasive sanitation treatment. The literature review of the following study showed that ozone and UVC rays are to be considered unanimously as the best virucides, bactericides, fungicides, insecticides, sporicides, and anti-molds.

Indeed, in the case of bacteria, ozone is recognized as having the ability to kill them. Concerning viruses, the scientific community is split. Some researchers affirm the ozone does not kill them, but it exerts an inerting action through oxidation of viral receptors with which the virus establishes the link with the cell wall and, therefore, with consequent inactivation of the invasion mechanism [1].

On the other hand, other researchers point out that ozone causes the killing of the virus [2] or, that after 30 seconds of exposure to an appropriate concentration of ozone, 99 % of the virus present are inactivated [3].
Besides, safe sanitizing properties are recognized with the ozone also towards mice.

When a mouse smells the ozone, it tries to escape quickly since its respiratory system can be seriously compromized in a short time, with consequent death.

However, the use of ozone leaves more than one perplexity when there is a subsequent presence of human beings in the environments as it is established that it can produce severe lung irritation if not carefully evacuated from the treated premises.

Starting from these assumptions, the D.I.M.E. / mcGEAR researchers have conceptualized a disinfection methodology capable of exploiting the advantages of the previous ones and overcoming their related flaws. This is obtained through a high-efficiency 4.0 machine designed to exploit the ability of certain lamps to ozonate the surrounding air by producing UVC rays with varying wavelengths. It follows that with a treatment lasting just a few minutes, at the end of which the ambient atmosphere is brought back to its original conditions without the need for special additional treatments, full sanitation of the environment is obtained.

This paper is organized into six sections. Section II provides a literature review of the main references used to develop this study. Section III introduces an overview of the

Chapman's cycle. The methodology followed during the creation of the new sanitizing system has been introduced in section IV. Section V illustrates the testing phase in different application with the related challenges whereas the conclusions have been presented in section VI.

II. Literature Review

This need prompted the researchers to study different procedures and methods such as Heating Sterilization [4], Ultraviolet Germicidal Irradiation (UVGI) [5], and chemical disinfectants [6][7]. Among them, ozone turns out to be effective in killing fungi, bacteria, molds, and inactivating viruses.

In this view, a literature review has been performed according to the following steps: (i) identification of the keywords and their combination; (ii) selection of a source database; (iii) results analysis. (i) The keywords selected are Ozone, sterilization, and virus and the search has been applied to Article Title, Abstract, and Keywords. In the second search step (ii), two different abstracts and citation databases of peer-reviewed literature have been selected: Scopus and Google Scholar.

The search has been narrowed down by considering only the most recent papers from the last ten years (2010-2020 included). During the third step (iii), a new systematic analysis of core specifics has been performed.

Tseng et al. identify surfaces as contamination sites of viruses, and they can contribute to their transmission to humans. Different techniques are available to sanitize surfaces, among them ozone plays a crucial role in the deactivation process of viruses even though this process is not fully known [8].

Cristiano states that ozone, thanks to its oxidizing property, is able to effectively destroy bacteria, fungi, and molds, and inactive many viruses both on the surfaces and suspended in the air. In particular, it is proved to inactivate SARS viruses but, there is no proof yet regarding the efficiency of ozone on COVID-19 [9]. By the way, since this is an envelope virus like all the Coronaviruses, this suggests the ozone might be effective also for COVID-19 [10].

Different studies show the effectiveness of the ozone in inactivating viruses using a relatively low ozone concentration (< 1mg/L) and short contact time (1min) [11] [12].

Some of the advantages and disadvantages of the ozone are introduced in the papers of Cristiano and Govindaraj et al. Among the advantages listed there are high germicidal efficacy on many organisms, high material compatibility, no toxic residues or emission, no manual handling of sterilant, low-temperature process, and self-contained monitoring. On the other hand, the corrosive nature of the ozone, and a lower efficiency on porous materials (such as textiles) appear among the drawbacks [9] [12].

Ozone is often generated in two ways: i) using ozone generators or ii) electrostatic air purifiers, both methods do not leave any poisonous residue [9].

An applicative advantage of ozone is the possibility to sterilize objects that cannot withstand high temperature or extreme heat such as facial masks [13]. In this view, Fischer et al. introduced the use of ozone as a method for the decontamination of N95 respirators making them reusable in case of shortage [14].

Rutala et al. provide a review of disinfection and sterilization methods in health care facilities. In particular, ozone finds many applications in the so-called Critical Items that are items with "high risk of infection if such an item is contaminated with any microorganism, including bacteria spores". Some examples are surgical instruments and cardiac and urinary catheters.

In such applications, most of the time, ozone has been mixed with Hydrogen Peroxide Vapor (HPV). This method has many advantages in terms of safety, toxicity (no toxic), compatibility with medical devices, and cycle time [15].

Agriculture is another interesting application field in which ozone is used, in this regard Ebihara et al. introduce ozone in chemical-free agricultural sterilization with the creation of an ozone-mist spray system. This involves the injection of the ozone gas into the water-mist produced by the water spray nozzle [16].

III. The Chapman's Cycle

The Chapman's cycle can be divided in two phases:

- Phase A: under certain wavelengths it splits the O2 into O + O which, combining with the other O2 present, form O3

- Phase B: under other wavelengths, the O3 are transformed back into O2 and O, restoring the initial situation.

More specifically, it occurs naturally under the effect of ultraviolet sunlight and shields harmful radiation (100-300 nm). The cycle consists of:

- Initial reaction of photodissociation, which occurs under the influence of solar rays with length less than 240 nm, i.e., O2 + HV (UV-C, L <240 nm) => O2 => 2O
- Ozone formation reaction, called propagation (1), is the exothermic reaction responsible for the thermal inversion of the stratosphere, i.e., O + O2 => O3
- Shielding reaction, called propagation (2), which causes ozone to be so important for the shield that it produces with respect to UV-B rays, i.e., O3 + HV (UV-C, UV-B, L <300 nm) => O2 + O
- Stop reaction or end of the cycle which is a very slow reaction that destroys the ozone, ending the cycle, ie O3 + O => 2O2

IV. Methodology

Considering the aforementioned Chapman's cycle, the researchers studied a series of systems aimed at satisfying individual sanitation needs.

A fundamental component is suitable UVC lamps with different wavelengths which, sequentially turned on by the operator, allow us to activate the different phases of the cycle.

This cycle produces, in the first phase, ozone in gaseous form thanks to it is possible to sanitize the environment and the furnishings present. Also, penetrating the fabrics (sheets, blankets, mattresses, curtains, carpets, carpets, ...) and into the smaller crevices (any cracks in the furniture, walls, floor, cracks in which viruses, bacteria, molds, spores, fungi, and insects can lodge).

This way, it would have been possible to have a highly effective sanitizing source without the drawbacks generated

by the ozone-steam mixture, when used in confined environments.
In particular, please note:

- potentially damaged wet surfaces
- Ozone to be evacuated before staying again in the treated environments

A. Equipment designed for sanitation

An essential element of this new phase of the study was therefore to identify a technological component that would make it possible the recreation of the Chapman Cycle for specific applications. Then, the problem became identifying the most suitable light sources on which to base the construction of machinery capable of reproducing this cycle, based on Engineering 4.0.

For this reason, a worldwide research campaign was started to find a lamp suitable for the current study.

At this point, it became possible to design a series of machines, one for each specific application, capable of allowing clean sanitization (i.e., without steam) at acceptable costs and such not to cause any damage to people, pets and things.

In this regard, the following machines have been conceptualized, designed, and built:

- Trolleys for floor sanitization
- Footboards for sanitizing footwear
- Box for sanitizing objects
- Drawers for sanitizing masks, keys, wallets, cell phones, money, ...
- Cases on wheels for the sanitization of shoes and tools
- Cabinets for sanitizing overalls, gowns, dresses, and various garments
- Multi-drawer trolleys for simultaneous sanitation and outpatient applications
- Stand (UVC-O3) for the sanitation of offices and infrastructures
- Combined towers (UVC-O3-liquids) for the sanitation of offices and infrastructures
- Wall lamp (UVC) for direct sanitization of small rooms
- Wall applique (UVC-O3) for ozone sanitization of reduced environments

In particular, these machines make use of fundamental elements of Industry 4.0 such as:

- IoT (monitoring and control via the Internet) and WEB portal (with dedicated interfaces accessible from any authorized device such as PC, laptop, desktop, smartphone, etc.)
- Sensors and telemetry for automated and reliable process management
- Analytics for data integration and analysis and their transformation into usable information

TABLE I
INACTIVATION OF BACTERIA, VIRUSES, FUNGI, MOLDS AND INSECTS

Organism	Concentration	Exposure Time
Bacteria	0.23 – 2.2 ppm	< 20 min
Virus	0.2 – 4.1 ppm	< 20 min
Fungi	2 ppm	60 min
Molds	0.02 – 0.26 ppm	< 1.67 min
Insects	1.5 – 2 ppm	30 min

This way, it will be possible to monitor instant by instant the effectiveness of the sanitization activity conducted.
Obviously, for areas in free air, such as roads, the ozone-steam mixture continues to work well, as the problems generated in closed spaces do not exist.

Pedestal multi-lamp machines, positioned inside the environment, allow the operator to sanitize the objects as well as the environment itself. At the end of the treatment, the environment can be readily re-habitable without the need of either further maintenance or drying and cleaning operations or waiting for the evacuation of the ozone. It should be noted places with a significant presence of ozone can irritate the respiratory system of the people present that, over a long period, could become chronic.

Figure 1 shows that the operator from a safe position, in order to avoid infection (from virus and/or ozone), is able to manage in parallel (at the same time) the sanitization cycle of several rooms through a remote Bluetooth control station able to operate, monitor and control several machines in parallel positioned in different environments.

The impact of this parallelization on operating times is huge since it allows the operator to halve the intervention time with only the use of two machines and proportionally to the number of machines used. According to table I [17-21], by counting about 30 minutes per cycle (i.e. about 5 minutes to reach the required concentration in parts per million, plus 20 minutes of the cycle, plus 5 minutes of reconversion of ozone into oxygen) the operator is able to sanitize 2 rooms in 50% of the time (2 rooms in 30 minutes are equivalent to a sanitation performance of one room every 15 minutes) 3 rooms in 33% of the time, 4 rooms in 25% of the time and so on up to a maximum of 5 machines in parallel.
The Bluetooth sensor is positioned in the most unfavorable point of the room, which is the one most distant from the machines, and has the task of ensuring the desired concentration level (peak and maintenance) during the execution of the cycle is reached.

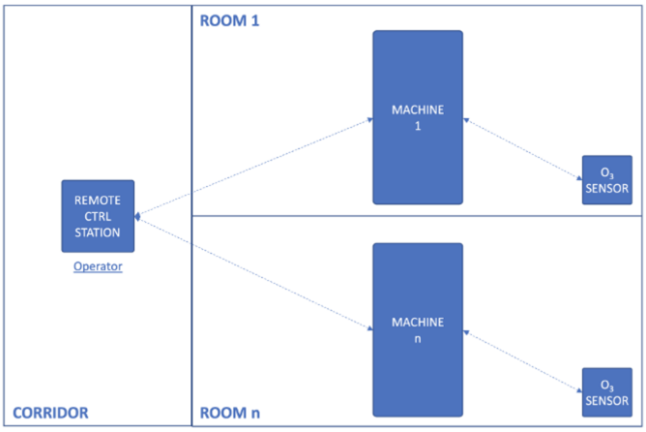

Fig. 1. Parallel sanitization cycle

In figure 2 we can observe how the operator, once again placed in safety from the possibility of infection as much as from exposure to the machines, can sanitize a large room. It is worthy to note that, by nature, the use of a single machine for the production of ozone, despite the use of special fans, is not suitable to sanitize an entire room since the ozone is not able to homogenously distribute itself in large volumes.

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The substantial difference between the process operated by the remote Bluetooth control station in Figure 1 and Figure 2 lies in the fact that in the first case manages n independent cycles for different environments, while in the second case the control unit is programmed to recognize the machines as one single machine operating only one cycle able to maintain the necessary ozone concentration (see Table 1) thanks to production and distribution of multi-spot ozone. In this case, a single ozone sensor for managing the process is used and it is always positioned in the most unfavorable point of the room.

B. Ozone Sensor Operations

An essential element of the proposed system is the ozone sensor fitted on a remote device with a wireless connection to the machine.
The sensor is positioned in the most unfavorable point of the room:

- as far as possible from the machine
- near a source of possible dispersion (windows, doors, transoms, breaches, ...)
- in niches or behind any bulkheads

The sensor continuously detects the concentration of ozone present in the environment (in ppm) and transmits the information to the machine. This way, the production of ozone continues until the concentration required for the inactivation of each agent to be sanitized (according to the values tabulated in the scientific literature) is reached.
The machine therefore closely monitors the time factor to ensure that the cycle can maintain the necessary concentration of ozone in the environment for the time required for sanitization.

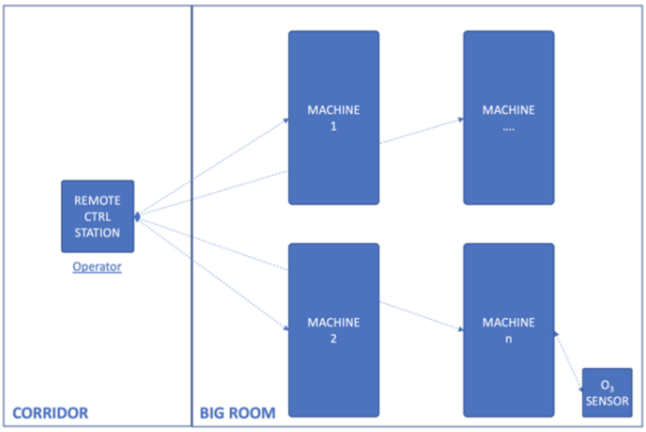

Fig. 2. Single room sanitization through multiple machines

If the ozone dispersions are excessive for maintaining the concentration of ozone needed to sanitize the environment, the sensor will block the machine to complete the cycle, so the printer associated with the remote control would issue a "partial cycle" receipt with no guarantee of sanitization.
It is proved that the sanitization operation is carried out correctly, therefore, it can be started the next phase of the Chapman's cycle namely, restoring the initial conditions of the environment with the reconversion of the ozone produced into oxygen.
When the cycle has completed the printer associated with the remote-control station will issue a receipt of successful operation with guaranteed sanitization.

V. TESTING

The machines were subjected to two types of tests: simulated (calculation) and laboratory (empirical through the use of sensors to check the concentration of ozone and chemicals through the sanitization analysis conducted on infected slides).
Such a campaign made it possible to conduct other robustness tests and to verify the application limits of the identified technology. It was therefore possible to confirm the absolute effectiveness of the machines within the recommended scope of application (confined and closed environments in which it is possible to reach certain levels of concentration). Where the level of ozone dispersion is too high and it is not possible to reach or maintain the necessary concentration for the time prescribed by the table values, needed to ensure sanitization, the proposed technology is not effective, therefore not applicable.
To overcome this problem, the DIME / mcGEAR Researchers studied and then integrated more technologies on the machines, so becoming capable of extending the spectrum of use to different areas of application (as described in the following paragraphs).

A. Robustness Test

The robustness test consisted of verifying the effectiveness of the lamps as the size of the environment to be sanitized grows (ratio time vs. dimensions). As described in the following paragraphs, it is worthy to note the non-linearity of the law that governs the number of lamps necessary to sanitize rooms of increasing size.

B. Limits

The application limits have been identified by positioning ozone detector sensors capable of measuring the dispersion of such gas in non-circumscribable environments.
Although the multi-spot application obtainable through the use of several equally spaced machines allows sanitizing larger environments, it should be noted that the action of ozone does not follow a linear law. This means that if an ozone lamp is sufficient to sanitize a 9 square meter space in 30 minutes, the sanitization of a double-sized room in the same time frame requires the use of more than two lamps. It follows that the convenience limit to the use of Ozone to sanitize large rooms is 4-5 machines (with 8 ozone lamps each) individually effective on a maximum of 45 square meters (225 square meters in total).

C. Sanitation of Corridors

The corridors, due to their shape (narrow and long) and nature (open on one side), do not allow to obtain either the diffusion or the concentration of ozone necessary to sanitize the environment. The use of ozone is therefore inadequate for this specific application.
In this regard, in order to quantitatively balance the performance of the Chapman's cycle, the machines are already equipped with several UVC lamps equal to those of ozone. UVC rays, that aims to produce and destroy the ozone in the Chapman's cycle, are delegated to have a sanitizing power no less than the one exercised from ozone, with the following limitations:

- Sanitization takes place by irradiation (the rays do not pass obstacles nor penetrate the tissues)

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- The power of the irradiation decays with distance (effectiveness less than 2.5 linear meters)

The limitations described above make it necessary to use ozone in confined environments with a diameter of more than 5 linear meters, containing obstacles (tables, chairs, furniture) and fabrics (mattresses, curtains, piles of towels, …).
The machines designed by the DIME / mcGEAR researchers are equipped with a "corridor kit" which requires a double installation (hardware and software) where:

- The hardware consists of:
  - a device that allows the vertical positioning of the UVC lamps during use in corridor mode for sanitizing walls and ceiling
  - 3 UVC lamps installed under the base of the machine for floor sanitization
  - the software excludes the Chapman's cycle by activating only the UVC lamps installed on the stem and under the base

By acting in this way, the machine allows the sanitization of the corridor in a single passage (floors, walls and ceilings) without waiting cycles, but with immediate effect allowed by proximity.
The application is particularly suitable for sanitizing narrow and long environments such as corridors (walls and ceiling at a distance of fewer than 5m in diameter from the UVC lamps) and similar environments (elevators, access sockets, ...).
The operator, duly protected by the use of PPE (Personal Protection Equipment) from exposure to UVC rays, leads the machine along the paths to be sanitized.
Although UVC rays cannot penetrate obstacles, tests conducted in the laboratory prove that the application is particularly effective on porous floors such as stone and on delicate floors like marble, carpet, parquet, ...

D. *Sanitation of large rooms*

Environments exceeding the dimensions recommended above are neither suitable for the use of ozone (the necessary concentration cannot be reached) nor for the use of UVC rays by radiation (distances exceeding the effective range).
This problem is found in large halls, stairwells, changing rooms, bathrooms, showers, lecture halls, theaters, stations, airports, auditoriums, etc.
In order not to limit the usability of the machines, the DIME / mcGEAR researchers have produced a version of the same machine integrated with a box capable of housing a double tank with a compressor and lance suitable for the nebulization of sanitizing different liquids.
It was decided to use two tanks to meet different needs (hydrogen peroxide is normally used for delicate surfaces and sodium hypochlorite for all the others).
A parking brake and a hose reel with rivelox hose have been set up to facilitate use in stairwells.

E. *Sanitation of External Environments*

The sanitation of external environments such as squares, and porches is similar to the sanitization of large environments by nebulizing liquids for disinfection.

VI. Conclusions

Beyond the scientific result obtained, certainly positive, this work demonstrates how in particularly complex situations of pivotal importance for the survival of many people (as it is the pandemic triggered by COVID-19), the cooperation of researchers with different scientific backgrounds can be extremely useful in developing new and effective solutions. In this case, using adequate knowledge of the behaviors of viruses, bacteria, molds, insects, and mice, as well as ozone chemistry (Chapman's cycle) and modern Engineering 4.0, it was possible to move from wet disinfection with all the drawbacks connected to it, to disinfection with gaseous ozone, produced by special machines directly in the places to be sanitized. Ozone does not generate problems for the environments and the objects contained in them and, at the end of the treatment, it leaves the environment free of itself and as such re-habitable by humans and pets. Given the results obtained, the researchers will continue the interdisciplinary collaboration on the presented topic.

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