Combination of UV radiation with 3D structure media filter for indoor air disinfection

Jiatao Liu¹, Junjie Liu¹*, Yingying Fan¹, and Pan Wang¹,
¹Tianjin Key Lab of Indoor Air Environmental Quality Control, School of Environmental Science and Engineering, Tianjin University, Tianjin 300350, China

Abstract. The ongoing COVID-19 pandemic made us re-realize the importance of environmental disinfection in indoor areas. Several studies have documented that the air purification system combining UV light and high-efficiency particulate air (HEPA) filtration can successfully remove the virus from the air. However, UV light cannot penetrate deep into the HEPA, which causes the pathogens inside cannot be killed. In this study, we analyzed the potential of three-dimensional (3D) filter media combining with UV sterilization for the treatment of pathogen aerosols. Through geometric ray analysis, it is concluded that the transmittance attenuation of 3D filter material is linear, while that of ordinary fabric filter material is abrupt, which means UV light combining with common fabric filter can only kill the microorganisms on the surface. In order to prove that 3D filter with UV irradiation can eliminate microorganisms inside the 3D filter, we carried out an experimental verification. The results of the experiment shows that the bactericidal rate increased with UV dose and the k value is 3.75*10⁻⁴, much smaller than that in air UV disinfection. This indicates that although it is more difficult to kill pathogens on the surface of fibers than in air, 3D filter material with UV can kill the pathogens inside.

1 Introduction

Particles of biological origin, such as viruses, bacteria, fungi that are floating in air are referred to as bio-aerosols which can cause serious health problems under some circumstance.[1] The influenza virus, severe acute respiratory syndrome, and COVID-19 epidemic are natural examples illustrating the profound, everyday impacts of bio-aerosols on public health.[2] Established technologies such as air filtration, and novel approaches such as UV light or plasma air ionization, have been proved having potential to reduce the concentration of the microorganisms in the air.[3-5] UV irradiation, which inactivates microorganisms by the formation of DNA/RNA dimers, shows great potential in air purification for its rapidity and effectiveness of sterilization.[4] The sterilization system using UV can be divided into three types, upper room (UR)-UVGI, in-duct (ID)-UVGI, and air purifiers with ultraviolet light. For UR-UVGI, although it can eliminate some airborne pathogens, it’s also a hazard for human health. For ID-UVGI, the germicidal rate depends on the UV exposure dose which is related to UV watts and exposure time. As a result, it’s hard for ID-UVGI to balance the air disinfection volume and sterilizing effect at the same time. For air purifiers with UV light, some researchers find that the combination of UV light and HEPA system can reduce the concentration of airborne pathogens effectively.[5] However, there is a notable paucity that the microorganisms inside the filter materials cannot be reached by UV radiation. Therefore, UV sterilization can only be effective on the first layer of HEPA filters. Therefore, to find a system that can effectively sterilize and eliminate bio-aerosols and will not produce secondary pollution can be well applied in air sterilization. Due to the outstanding air permeability, knitted filters with a three-dimensional (3D) structure have been developed and studied.[6, 7] Some research indicate that the permeability is relative to light transmittance.[8] However, few studies have explored the light transmittance of 3D filter materials. In this study, the potential use of a novel three-dimensional knitted spacer air filter (3D filter) for combining with UV light for air disinfection, which can overcome these challenges, was theoretically and experimentally investigated.

2 Materials and methods

2.1 Novel three-dimensional knitted spacer air filter (3D filter)

The 3-D filter was one kind of warp knitted spacer fibrous medium.[6] The 3D filter materials we use has three layers. The basic fiber information was obtained from the SEM images shown in Fig. 1. The average value of the fiber diameter is 44.4 µm. The thinness of the 3D material is 3.0mm. And the porosity of the 3D material is 91.9%.

* Corresponding author: jjliu@tju.edu.cn

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From Fig.1, we can see the front layer with many holes is a structure of connected loops knitted by a succession of multifilament of twisted fibers. The back layer is also knitted by loops in string of multifilament and tighter than the front layer. The inner layer is spacer yarns connecting front layer and back layer. The thickness of the three layers is 0.16 mm, 2.3 mm, 0.322 mm, separately. As a consequence, the modeling structure of 3-D filter was composed of three layers as shown in Fig. 2.

The porous structure of 3D filter material leads to better air permeability than other filters. The European standards EN779[8] and EN1822[9] classify air filters from G1 to U17 according to filtering quality. We choose three kinds of filter materials, G3, M5 and F7, to measure of the difference in filter performance in pressure drop and filtration efficiency. The results are shown in Figure 3. When the particle size is more than 3μm, the filtration performance of 3D filter is higher than 80%. Fig. 3(b) shows that when at same air velocity, the pressure drop of 3D filter is the smallest.

2.2 Ultraviolet transmittance

We use a Geometric optical calculation simulation software, Tracepro, to calculate the intensity of light at different depths of 3D materials. TracePro can accounts for absorption, specular reflection and refraction, scattering and aperture diffraction of light. The process of ultraviolet transmittance simulation is as follows. First, import the geometry of filter material unit into Tracepro software. Second, set the light source and material properties. Set the light source parameter: 275nm wavelength, intensity 31W/m², parallel incident. 3D filter fiber is PET material. Through literature search, we determined the reflection constant to be 0.2,[11] and the absorption constant is 0.8. Thirdly, set virtual surfaces to show results. In this study, we set up 26 virtual light receiving surfaces for presenting the final light receiving result. The simulation process is shown in Fig. 4.

2.3 UV disinfection

The UV efficiency varies across separate pathogens in different situation. Applying the first order Chick Watson model, the Log Reduction Value (LRV) can be
described as a equation of k and UV dose. The equation is as follows.

\[
\log \left( \frac{N}{N_0} \right) = k \times UV \text{ dose}
\]

Where \(N/N_0\) indicates the proportion between the number of microbes after and before UV irradiation. \(k\) indicates the virus inactivation rate constant (cm²/mJ) to describe inactivation. A higher value of \(k\) displays the increased sensitivity of the virus at a particular wavelength. UV dose (D) indicates the radiant exposure per unit area or fluence (mJ/cm²) at a particular wavelength (\(\lambda\)).

The UV dose is also an important factor in UV irradiance-based microbes inactivation. It can be calculated as the product of UV radiate flowing (I) and contact time. The equation for the UV dose can be expressed as follows:

\[
(\text{Em})/\text{cm}^2 = 1 \text{W/m}^2 \times \text{time(s)}
\]

2.4 Experimental setup and operating conditions

2.4.1 Microbe

E. coli is a common strain. The biochemical characteristics of E. coli have been well understood. In addition, the UV sensitivity of E. coli has been tested in literature, so we chose E. coli (ATCC 25922) as experimental bacteria in this study to verify the accuracy of theoretic analysis in practice.

2.4.2 UV light sources

Two kinds of light sources were used in the experiment: the 30W mercury vapor UV lamp with a wavelength of 275nm and the UV LED lamp with a wavelength of 254nm. At the surface of the first layer, light intensity at 275nm and 254nm is 31.0W/m² and 30.3W/m² separately.

2.4.3 Experimental process

First of all, E. coli were grown in Trypticase soy broth at 37 ℃, the optimum growth temperature of E. coli. After 18 hours culturing, when the bacteria content is \(1 \times 10^3\) cfu/ml-3 \(10^5\) cfu/ml, prepare bacterial suspension. Then, the bacteria suspension droplets were placed on a 3D filter material of 1*1cm² as the bacterial tablet. Secondly, as shown in Fig. 5, illuminate the bacterial tablet with an UV lamp (or UV LED). After all exposures were complete, 5.0ml of diluent was absorbed into a sterile small dish, placed in a water bath at 20℃ ± 1℃ for 5min. Then a bacterial tablet was clipped with sterile tweezers and soaked in the diluent. After treatment for 10min, remove the slices with sterile forceps immediately, and transfer them into a test tube containing 5.0ml diluent, mix them for 20s with an electric mixer. Select Suspension with appropriate dilution and absorb 1.0ml, respectively, and inoculate it in a plate for viable bacteria culture counting. Additionally, the same operation was performed on the bacterial tablet without UV irradiation, as a blank control.

![Image](https://example.com/image1)

**Fig. 5.** The process of sterilizing the 3D filter containing bacteria by UV irradiation.

3 Results

3.1.1 UV light intensity at different depths

Fig.6 is the irradiance analysis diagram after UV passing through the unit filter material. Through calculation, after passing through the overall filter material, the light intensity attenuates to 26.96% of the incident.

![Image](https://example.com/image2)

**Fig. 6.** Irradiation analysis diagram after unit filter material.

Fig.7 shows the curve of the average intensity of irradiance varying with the depth of the filter material. It can be seen that the first and third layers have strong shielding power on light. The shielding of the first layer attenuates the irradiation intensity by 29.92%, the shielding of the third layer attenuates the irradiation intensity by 21.62%. The thickness of the middle layer is the thickest, however, the shielding of the middle layer only attenuates the radiation intensity by 22.28%.

Additionally, shown in Fig.7, the relationship between the middle layer and illuminance and attenuation percentage is approximately linear. According to the linear fitting, the slope after fitting is: the slope of correlation between thickness and illuminance is -0.00235, and the slope of correlation between thickness and attenuation percentage is -0.00757.

![Image](https://example.com/image3)

**Fig. 7.** The process of calculating parallel light incident 3D filter material.
3.1.2 The overall bactericidal effect of UV on 3D filter material

Fig. 8 shows the results of E. coli inactivation varying with irradiation time. The figure indicates the average results, expressed as log inactivation. The k value is calculated to be 3.75*10^-4, which is much smaller than that in air. This means, microorganisms on the surface of 3D filter are less sensitive than those in air. Moreover, because the bacteria are deep in the 3D material, the infection results indicates that UV light can eliminate the microbes inside the 3D material.

![Fig. 8. UV inactivation curves of E. coli in dependence on irradiation time.](image)

Fig. 9 shows the Log Reduction Value (LRV) of E. coli at different wavelength under 30 min UV exposure.

Fig. 9. Log Reduction Value (LRV) of E. coli at different wavelength under 30 min UV exposure.

4 Conclusions and discussion

Additionally, Fig.9 shows the Log Reduction Value of E. coli at different wavelength under 30min UV exposure. The results indicate that E. coli are more vulnerable at the wavelength 275nm. Which means UV at 275nm may be more easily absorbed by DNA of E. coli and cause crosslink between two thymine bases. In this study, we analyze the potential of UV light combining with 3D filters in the future use in air disinfection. Light transmittance of 3D filter material was calculated using the basic principles of geometrical optics. The results show that, there is a linear relationship between the thickness of the inner layer and the light transmittance, while the relationship between the thickness of front or back layer, also known as common woven filter material, and the light transmittance is a leap. This indicates that normal woven filter materials can only get UV irradiation on the surface, but not in the interior, which means when use the UV light to eliminate microorganisms, the inside microbes cannot be inactivated. However, 3D material, especially the inner layer, has a good transmission effect on lights. As a consequence, 3D filter material have a great potential on UV disinfection. Moreover, we have a preliminary experimental verification to prove that UV light can enter the interior of the 3D filter material to kill microbes. The results shows that UV inactivation curves of E. coli in dependence on irradiation time conforms to the first order Chick Watson model and the k value is calculated to be 3.75*10^-4. This indicates that the UV light can kill the microbes inside the 3D material. Nevertheless, this study still has some deficiency in simulation calculation. Further study should consider combining the deposition effect and the transmittance to calculate the theoretical sterilization rate on 3D filter.

References

2. L. Morawska, J.Cao, Environ Int. 139, 105730 (2020)
8. STANDARD, BRITISH. "High efficiency air filters (HEPA, HEPA and ULPA).", (2009).