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Improvement of ultraviolet C decontamination rate using composite quartz metamaterial

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Abstract

A new method for repackaging optical metamaterials formed from quartz spheres/fibers of various diameters is proposed for ultraviolet C disinfection of infected liquids by pathogens (viruses and bacteria). © 2022 The Author(s)

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Keywords: Pathogen; UVC Decontamination; Quartz metamaterial; Repacking procedure; Decontamination volume

1. Introduction

The increasing popularity of metamaterials and their application in fluid decontamination, open up amazing possibilities for their use both in decontamination and in the actual handling of pathogens (viruses and bacteria) that spread together with the contaminated fluid (water, blood, blood plasma, air, gases) among the elements of the metamaterial. In comparison with earlier proposed equipment's [3–5], our investigation is are focused in the applying of various geometry of packing elements. The comparison of these packing procedures brings to the improvement of the UVC decontamination contact surface with fluids and gives an expected result in the decontamination rate. We also will propose the new more compact decontaminates for liquids and gases based on the idea of the construction of composite metamaterials from micro- to nano- skills using the optical contact between synthesized metamaterial elements with various structural dimensions using repacking technologies. Here it is proposed to combine thick and thin elements of composite metamaterials formed from quart spheres or optical fiber in order to achieve the expected results in decontamination efficiency. For this, we revised all packing structures formed by the bubbles /fibers packing method. We are interested in declining of the space between the big elements of metamaterial which is not penetrated by the UVC radiation. This space may be expressed through the balls packing density in each quasi-periodical cell, where the cell density, depends on the packing structure of the metamaterial. For example, in the hexagonal lattice arrangement, this density is equal to which is larger than tetrahedral lattice packing one (see Fig. 1). Taking into consideration the efficiency of the decontamination contact surface between the elements of the metamaterials-like photonic crystals or photonic crystal fiber described in our experiments [3–5], we propose to use the combination of elements of metamaterials like spheres/fibers in the close packing procedure which form in principle the good material for the propagation of UVC radiation and flows of contaminated liquids/gases penetration in it.

In order to improve the penetration of the UVC radiation inside the liquids we first proposed to minimize the elements of quasi-periodical dispersion structures. This minimization of elements of metamaterial gives us increases in the free decontamination volume (or surface) inside the system, which is proportional to the penetration deeps of the

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evanescent field of UVC radiation from the elements of metamaterial inside the fluid multiplied to the total surface of metamaterial elements. At first, glance appears the idea that if we will drastically reduce the diameter of the quartz spherical elements or fiber elements of metamaterial, we can increase the contact surface. But this idea won't work for the necessity of deeper penetration of radiation inside the contamination fluids due to the existence of two inconvenient effects connected with the higher scattering of the UVC radiation on the surface of metamaterial elements formed from the quartz spheres/fiber with small diameters and increasing of the flow resistance of the liquid/gas inside the metamaterial. In this situation, the effective decontamination volume of metamaterial penetrated by contaminated fluid will be non-efficiently used. The laboratory observations demonstrate that the increase of the reflection from contact between the elements of metamaterials practically becomes an obstacle in the deeper penetration of radiation inside it. The combination of the big and small elements of metamaterial helps us to avoid the above obstacle.

The free volume in the above example is so that in cubic packing of spheres, we have more free space than in a hexagonal one. Following this example, we want to find the efficient decontamination volume, which is proportional to the contact surface of the contaminated liquid with such packing balls. Taking into consideration that the penetration depth, $\kappa \sim \lambda/[2\pi\nu\sqrt{n_m^2 - n_f^2}]$, of UVC radiation on the free space between the balls is proportional wavelength of radiation and inverse proportional to the difference between the square values of refractive indexes of metamaterial, n_m, and fluid, n_f , we easily find this effective volume, $V = \kappa S$. We observe that this volume is smaller than the free volume between the balls. As the decontamination efficient volume around the ensemble of packing balls is proportional to the

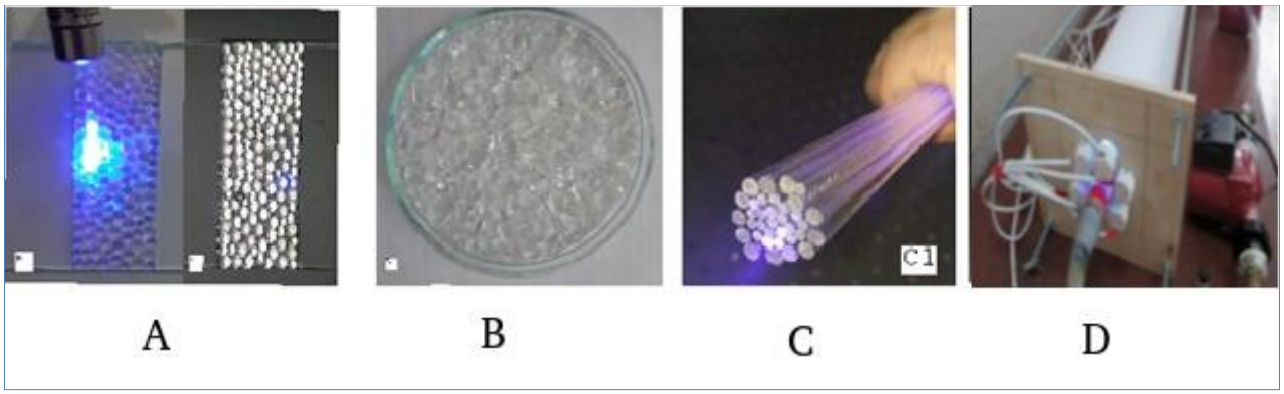

Figure 1 The realization of the close random packing of the small and big spheres (fibers), which we proposed in our experimental measurements. 1A corresponds to the blue laser radiation of the sample and 2A without blue laser radiation. Figure B corresponds to the metamaterials formed from dropped quartz with different dimensions from 10−5 mm to 1−2 mm. Fig C, represents the packing of two types of optical fibers proposed for the decontamination core of the equipment. So the free non-penetrated by UVC radiation space between the elements of each material achieves minimal value. Fig. D represents the decontamination equipment with open core described in Ref. [4]

Penetration depth of UVC radiation and inverse proportional to the diameter of the balls, we observe that only for the small diameter of the spheres balls it can achieve the free volume between the balls described by the free volume. For the wining in the contact surface and penetration depth, we propose to repack these structures with the sampler balls as this is represented in Fig. 2 A and B. The repacking structures must be in optical resonances between the gallery modes of each sphere/fiber subsystems in closed packing as this Fig 2 A, B, C. Not so larger estimations show us that for the big ball diameters and large spectral radiation of UV surfaces practically these resonances are possible and experimentally observed (see Fig. 3). In Fig.2 A, B it is represented right expresses the possible resonance between micro-spheres with different dimensions when the light wave can regard as a standing whispering-gallery-mode (with its own eigenstate). This gallery penetration of the radiation can be also used between close packing procedures of optical fibers with different thicknesses, respecting the conditions of guiding the waves through them represented in Fig.2 C. When we fill up the free space between the elements of metamaterial with other small elements, it is observed that the total surface of two species of balls, $S_u = S_{u1} + S_{u2}$. Here $S_{u1} = \pi^{d_1 2} N$ and $S_{u2} = \pi^{d_2 2} N$ are the total surfaces of each species of the spheres. The diameter$\sqrt{}$ d_2 depends on the close repacking of tetrahedral structures, $d_2 = (\sqrt{3}/2 - 1)\, d1$ or cubic $d_2 = (3-1)\, d_1$, represented in the Fig.2. We not that the small spheres with diameter, d_2 are situated in the center of the cubes/the trader of the big one and don't have direct contact between them.

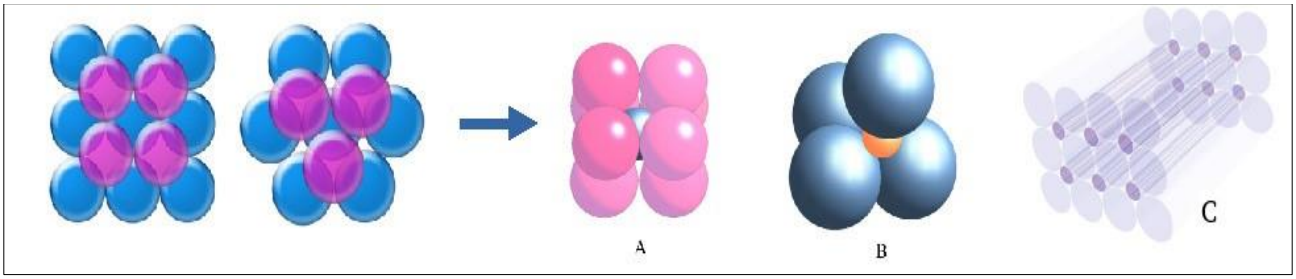

Figure 2 The close spheres/fibers repacking procedures on the space: cubic (A)/square(C) and Hexagonal (B) repacking possibilities

2. Experimental Estimations and Analyses

The core of the equipment proposed in the Refs. [4, 5] is adapted to the new conception of the repacking of studied metamaterial small quartz balls/fibers between the big one. Taking into consideration that the big number of pathogens are sensible to UVC radiation than eukaryotic cellular structures, we had to substitute these contaminated dangerous fluids with yeast solution, which has larger resistance to UVC radiation in comparison with many viruses or bacteria. In this approach, the improving of the inactivation rate of the yeast colony using these types of metamaterial represented in Fig. 1 will mean that the proposed efficient method will work successfully well in the case of prokaryotic cells specific for many bacteria. In the experimental results in Fig.3, we estimate the decontamination rate using the granulated spherical metamaterial with diameter about 2 mm repacked with another type of spheres with diameter about 1 mm. In the Fig 4 the decontamination core represented in Fig. is filled up by the mixture of the granulated quartz material with large dispersion in the mean value of the granule dimension (from 0.01 cm to 0.5 cm) represented in Fig. 1B demonstrate the big decontamination rate in comparison with the mixture of big and small spheres or fiber system repacked (see Figs. 1 and 2 and experiment in Figs. 4). We also have filed up the decontamination core with two types of fiber with diameter about 1 mm and 0.5 mm. The similar experimental results is presented if the Fig. 5, where the repacked fiber improve the decontamination rate. As follows from the first experimental results the composed metamaterial gives a substantial increase in the decontamination rate in comparison with homogeneous one formed from the elements with the same dimension and topological form [4, 5].

Figure 3 The left figure represents the various dimension of yeast fungus colonies before going through the decontamination equipment consisted of the core tube with a diameter of about 3.0*cm* and length 1.0 *m* filled up with quart meta-material consisted from big spheres with diameter, 1 mm, repacked by small spheres with diameter about 0.5 *mm* represented in Fig.1A. The central figure represents the yeast fluid visualized on the optical microscope after its passing through the decontamination equipment during the 5 *min*. As it is observed the optical microscope practically doesn't detect the yeast fungus. The right figure represents the increase of fungus colonies in the same"decontaminated" fluid after one day (24 hours). It is observed a slight increase of the yeast colonies during one day

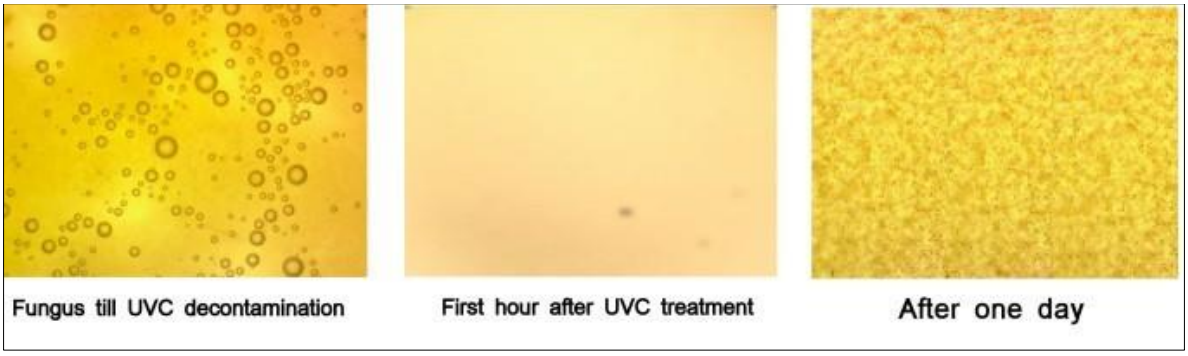

Figure 4 A similar three figures were obtained for the decontamination core filled up with granulated metamaterial with a large variety of granules. It is observed that after one day the mean value of the new restoration colonies of the yeast fungus is smaller than in bubbles packing

In the above experiments was taken $2.1L$ of water in which was dissolved $80Gr$ of yeast and added $440Gr$ of sugar. After 10 Min the dynamical (see Fig. 3) experiments began. Our decontamination core with 0.8 M length and 2.5 cm in diameter is filled up with a diameter of spheres/fibers about 0.5 -1 mm of the quartz material. The core is covered by 6 mercurial lamps which a maximum of radiation is 250-260 nm (see Fig. 1D). To improve the efficiency of UVC radiation all the system is placed in the aluminum cylinder with the diameter about 20 cm so that the intensity of the radiation in the center of the big cylinder increase significantly due to the reflection proprieties of the aluminum [4,5].

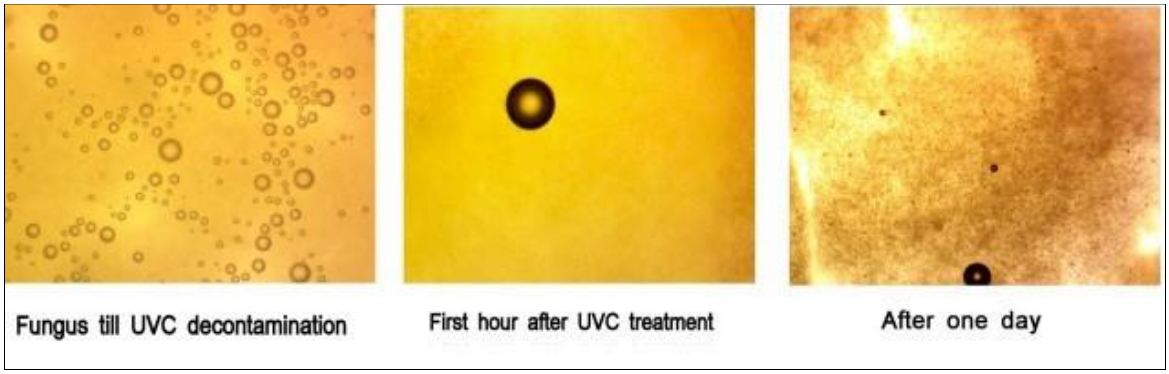

Figure 5 The last two figures (central and right) represent the decontamination procedure with two types of packing fibers in the decontamination core. As it is observed after 5 min of the UVC radiation some colonies continue to remain in the fluid. This is connected with the remaining large intervals between the fibers during the laminar flow of the yeast liquid

More than this the researchers and people from the room are well protected from the direct action of UVC radiation obtained from 6 lamps.

3. Conclusion

Application of UVC radiation for decontamination of surfaces by viruses and bacteria requires an urgent and effective method of interaction of radiation with microorganisms described above. Open surfaces can't give us the expected result in this area. If optical fibers are separated, then this surface consists of fiber length multiplied by the length of the base perimeter. These surfaces per volume increase if such optical systems are arranged in the periodical optical structures with good optical contacts between them. In this situation, we must get a supplementary surface and good distribution of UV radiation through all volumes. In this case, we must estimate the adherence of the liquid to this surface, the penetration distance of the evanescent field in the liquid, absorption of UV radiation by the bacteria and other microorganisms from this contaminated liquid. On the basis of this effect in our laboratory was elaborate two equipment for the decontamination of infected liquids and gases. Experiments have conclusively demonstrated that both quartz spheres and optical fiber metamaterials can effectively annihilate Coliform (including Escherichia coli), or Enterococcus bacteria, as well as yeast and Kombucha cultures.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors of this manuscript worked together on the preparation of yeas solutions and equipment for inactivation. We don't have the financial, commercial, legal, or professional relationship with other organizations, or with the people working with them, that could influence our research.

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