SANUVOX
PURIFYING AIR AT THE SPEED OF LIGHT™

Sanuvox Technologies Inc.
146 Barr.
St-Laurent, Qc.,
H4T 1Y4

p. 1.888.726.8869
f. 1.888.582.6475
e. info@sanuvox.com

Technical Report:

Simulation of the air disinfection performance of Effectiv HVAC diffuser equipped with Sanuvox Technologies LMPHGJ105-UVC-254 nm

Normand Brais Eng., M.Sc., Ph.D.

October 17 2021

Content

Sanuvox Technologies Inc.
146 Barr.
St-Laurent, Qc.,
H4T 1Y4

p. 1.888.726.8869
f. 1.888.582.6475
e. info@sanuvox.com

1-Introduction

Sanuvox Technologies being the germicidal UV system supplier of EffectivHVAC, our engineering has proceeded to the simulation of their diffuser to determine the delivered germicidal dose and consequently the expected disinfection performance over a wide range of airborne microorganisms.

2-Air diffuser geometry and UV source

The air diffuser is a typical 24'' x 24" ceiling mounted unit where our special J-shape UV source LMPHGJ105 is installed as shown in fig.1 below. The UV source has a specific output power of 0.31 Watt/cm, and a total UV output of 14.2 Watt at a monochromatic wavelength of 254 nm. This wavelength being above 240 nm cannot generate any ozone. The diffuser is equipped with a set of baffles to prevent any stray UV rays from escaping the enclosure.

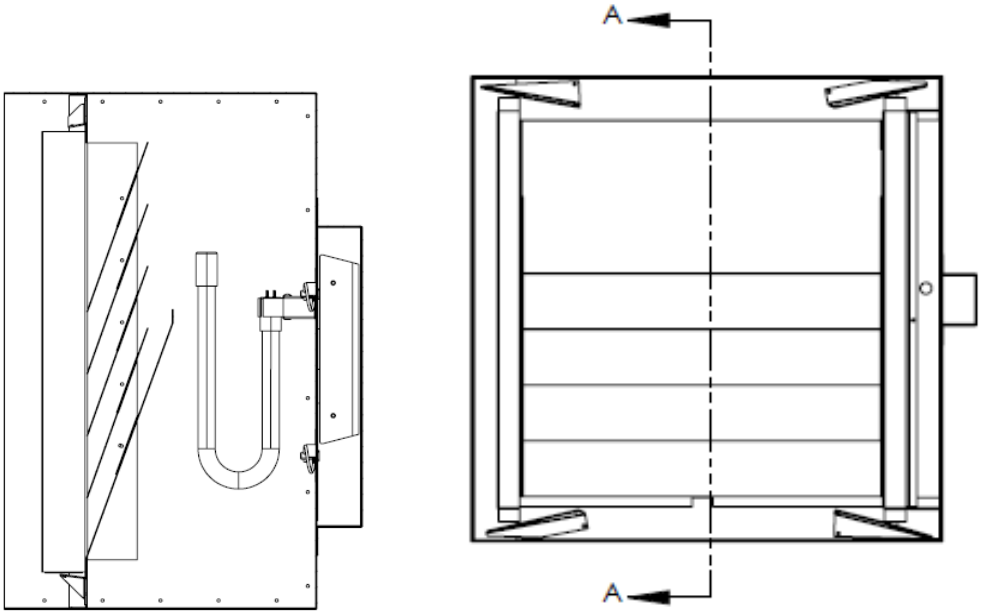


Fig.1 Cut view of simulated air diffuser with single UV source

3-UV Dose Simulation Calculations

The UV irradiation field can be calculated by summation inside a duct where the lamps are placed parallel to the air stream, thus minimizing windchill effect on the lamps:

Sanuvox Technologies Inc.
146 Barr.
St-Laurent, Qc.,
H4T 1Y4

p. 1.888.726.8869
f. 1.888.582.6475
e. info@sanuvox.com

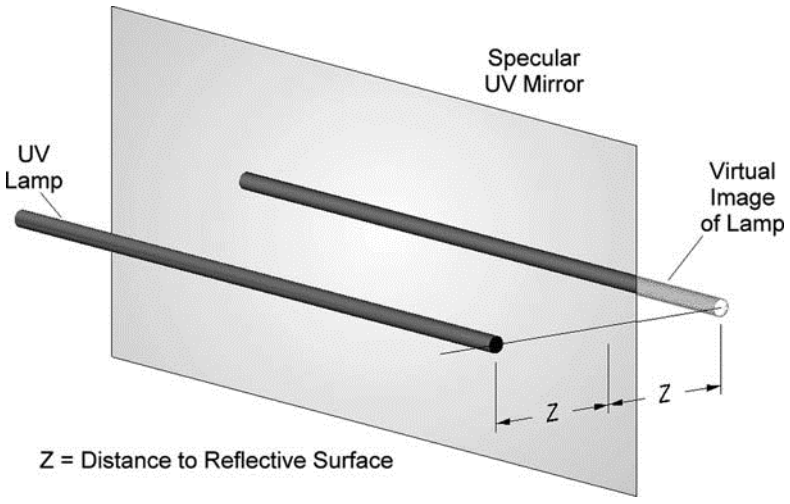
$$UV_{field}(x, y, X_i, Y_i) = \frac{\frac{P_{UV}}{L_{arc}}}{4 \cdot \pi \cdot V_{air}} \cdot \left[\int_{L_{inf}}^{L_{sup}} \int_{0}^{L_{arc}} \frac{1}{(z - L)^2 + \left[[x - (X)]^2 + [y - (Y)]^2 + r_{bio}^2 \right]} dL\, dz \right]$$

Where X_i and Y_i are the coordinates of each lamps inside the duct and where L_{inf} and L_{sup} are the longitudinal summation boundaries. Also, V_{air} is the air velocity inside the duct and r_{bio} is the radius of Biowall unit.

The superposition of the contribution of each UV sources inside the duct is the sum of the emission field of each lamp as follows:

$$UV_{total}(x, y) = \sum_{i=1}^{N} UV_{field}(x, y, X_i, Y_i)$$

When reflectivity is high (75-85% for polished aluminum) and the reflective surfaces enclose most of the chamber area which is the case here, the resulting reflections allow for a significant contribution to the total UV field. These reflections that echo between surfaces are called inter-reflections. The resulting intensity due to the inter-reflections will achieve steady state at the speed of light, converging to a finite value that depends on duct geometry and inner surface reflective properties.



The physical process of inter-reflections can be simulated by using a computer model performing enough iterations, in practice only the first reflection is used to remain conservative. Neglecting to use highly reflective duct lining surfaces such as polished aluminum severely impairs UV system

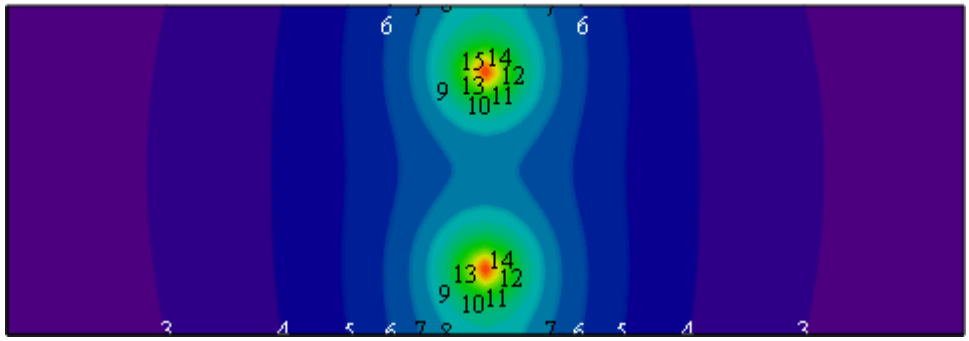
Sanuvox Technologies Inc.
146 Barr.
St-Laurent, Qc.,
H4T 1Y4

p. 1.888.726.8869
f. 1.888.582.6475
e. info@sanuvox.com

performance by a factor of two or more for the same input power. The efficiency increases just about linearly with the surface reflectivity as expressed in the following final equation.

$$UV_{total}(x,y) = \sum_{i=1}^{N} UV_{field}(x,y,X_i,Y_i) + Reflex_{coeff} \cdot \sum_{image} UV_{field}(x,y,X_{image},Y_{image})$$

Delivered UVC Dose (mJ/cm2) for 300 CFM air flow



UViso

$$Min_{UV} = 2.347 \frac{mJ}{cm^2} \qquad AVG_{UV} = 4.44 \cdot \frac{mJ}{cm^2} \qquad Max_{UV} = 19.7 \cdot \frac{mJ}{cm^2}$$

4-Dose-response relation and expected disinfection rate

In order to understand the UV disinfection process, it is helpful to consider UV as the analogue of a bombardment of photon bullets on a microbe. Each photon carries an amount of energy called a quantum E_λ, of a value connected to the light wavelength according to the Planck-Einstein relation :

$$E_\lambda = h\,c/\lambda \qquad \text{Eq.(1)}$$

Where

Sanuvox Technologies Inc.
146 Barr.
St-Laurent, Qc.,
H4T 1Y4

p. 1.888.726.8869
f. 1.888.582.6475
e. info@sanuvox.com

h = Planck's constant, 6.626 x 10^{-34} Joule.sec

c = Speed of light in vacuum, 2.998 x 10^{8} m/sec

λ = wavelength, m

Using the Planck-Einstein relation, the energy conveyed by each UV-C photon at a wavelength of 253.7 nm is equal to 7.83 x 10^{-19} Joule. Therefore, the number of photons per Joule is the inverse i.e. 1.28 x 10^{18} photons per Joule. Remembering that one watt of power is defined as a rate of one joule of energy per second, then a UV intensity of 100 Watt/m^2 provides a flow of 1.28 x 10^{20} photons per second per square meter.

Now, considering that a virus of 0.1 micron diameter like SARS-CoV-2 has a cross-sectional area of 0.785 x 10^{-14} m^2, despite its tiny size, this virus will be bombarded by 1 million photons per second. Given a sufficient duration time to this UV photons assault, photochemical damages will accumulate enough to render the organism biologically dysfunctional.

Regardless of the tremendous number of photons shooting at this virus, only a very small number hit their target successfully to initiate the photochemical reactions. The real effective inactivation cross sectional area of a target microbe is a function of many parameters, among them, the quantum chemical yield, the outside capsid protective layers, and the distribution of its nucleotides sequence. A promising predictive method based on the above described photon bombardment concept and successful hit probability has been published to predict the UV susceptibility of microorganism as a function of their genome without using standard elaborate lab procedure. [(14)]

Based on the above described UV bombardment analogy, a mathematical relation can be written to express the UV dose response for a population of bio-organisms. It is reasonable to infer that the rate of decay of a microbial population will vary proportionally to the number of successful hits over a period of time. This rate of successful hits can be described as the product of the UV power per unit area **I**, the number of bio-organism **N**, the bio-organism effective UV inactivation cross section **k**, also called the bio-organism UV susceptibility constant, and the exposure time **t** as follow:

$$\textbf{Hit rate} = \frac{dN}{dt} = k\,N\,I\,t \qquad \text{Eq. (2)}$$

Integration of equation (2) yields:

$$N(t) = N_0 e^{-kIt} \qquad \text{Eq (3)}$$

Sanuvox Technologies Inc.
146 Barr.
St-Laurent, Qc.,
H4T 1Y4

p. 1.888.726.8869
f. 1.888.582.6475
e. info@sanuvox.com

Where

N_0 = initial number of microorganisms,

N_t = number of microorganisms surviving after any time t,

k = a microorganism-dependent UV susceptibility constant, in m^2/Joule,

I = the irradiance UV intensity received by the microorganism, in Watt/m^2

t = exposure time, in seconds

The fraction of the number of microorganisms initially present, which survive at any given time, is called the survival ratio S and can be expressed as:

$$S = \frac{N_t}{N_0} \qquad \text{Eq(4)}$$

The sterilized fraction is what is called the disinfection rate, is simply 1 minus the survival ratio.

$$Disinfection = 1 - S = 1 - e^{-kIt} \qquad \text{Eq(5)}$$

As explained, we can define the germicidal UV dose by the total number of UV photons emitted per unit area during a time interval, which can be written as:

$$UVDose = I \times t \quad \text{in Joule/m}^2 \qquad \text{Eq (6)}$$

By substituting eq.(6) in eq.(5), we finally get the stndard germicidal UV Dose-Response relation:

$$Disinfection = 1 - e^{-k\,\mathrm{UVDose}} \qquad \text{Eq (7)}$$

What equation 7 illustrates is that a given dose produces a predictable disinfection rate, whether the UV dose consists of low UV intensity for a long exposure time, or a high UV intensity for a shorter time. A key difference between surface decontamination and airborne inactivation of organisms is exposure time.

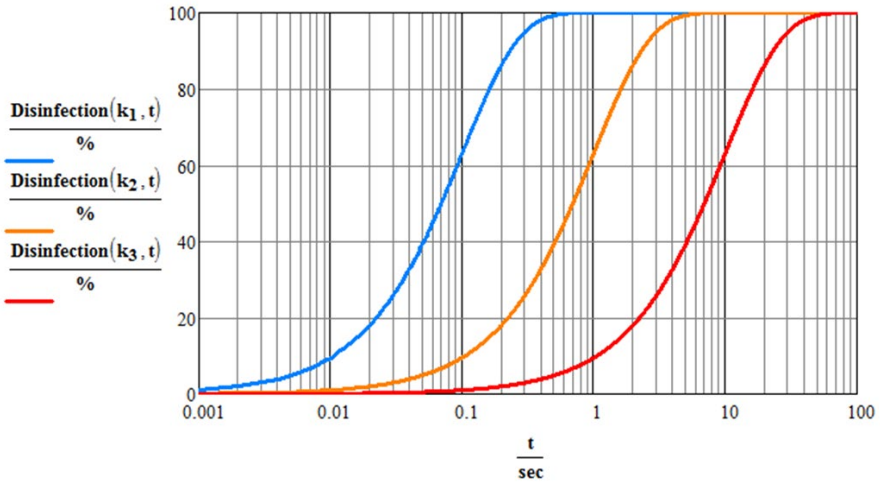
Sanuvox Technologies Inc.
146 Barr.
St-Laurent, Qc.,
H4T 1Y4

p. 1.888.726.8869
f. 1.888.582.6475
e. info@sanuvox.com

The exposure time for any in-duct disinfection will be of the order of a second or a fraction of a second depending on airflow velocities. Therefore, the UV intensities for neutralization of an airborne microorganism need to be orders of magnitude higher than that typically used for stationary surface disinfection such as walls or air-conditioning cooling coils.

Equations 3, 5, and 7 shown in figure 5 describes an exponential decay in time of the number of living organisms as a constant level of UVGI exposure intensity is applied. The very same type of equation is used to describe the effect of chemical disinfectants on a population of microorganisms, with the dose in this case being a chemical concentration multiplied by a contact time.

Fig.5 Disinfection rate –vs- UV exposure time for various UV susceptibility



Within the limits of experimental accuracy, the lethal action of germicidal UV appears to be independent of the nature of the organism and, unlike antibiotics, there has been no signs of adaptive resistance after over fifty years of monitoring for water disinfection.

Susceptibility of microorganisms to UV photons

Organisms differ in their susceptibility to UV inactivation. A few examples of familiar pathogenic organisms are included in each group for reference. It is important to note that it is impossible to list all the organisms of interest in each group. Depending upon the application a public health or medical professional, microbiologist, or other individual with knowledge of the microbial threat or organisms of concern should be consulted.

In general, vegetative bacteria are the most susceptible to UV, followed by mycobacteria, then the bacterial spores and finally the fungal spores which are the most resistant to UV energy. Within each group, an individual species may be significantly more resistant or susceptible, so care should be taken using this ranking only as a guideline. It should be noted

Sanuvox Technologies Inc.
146 Barr.
St-Laurent, Qc.,
H4T 1Y4

p. 1.888.726.8869
f. 1.888.582.6475
e. info@sanuvox.com

that the spore forming bacteria and fungi, also have vegetative forms which are markedly more susceptible to inactivation than the spore forms.

Viruses are particularly problematic to categorize as their susceptibility to inactivation is even broader than that of bacteria or fungi.

By inspection of Eq. (5), larger values of k represent more susceptible microorganisms and smaller values represent less susceptible ones. Units of k are m^2/Joule which is the inverse of the units used for UV dose.

For example, the value of the UV susceptibility of Influenza-A virus has been measured experimentally by Jensen in 1964 and was found to be 0.0119 m^2/J in air at 68% relative humidity. Based on this value, one can determine the required UV dose to be applied to reach at least 90% disinfection of a population of influenza-A virus using the following formula:

$$\boldsymbol{D90} = \frac{\boldsymbol{ln(10)}}{\boldsymbol{k}} = \frac{\boldsymbol{2.30}}{\boldsymbol{k}} \quad \text{in J/m}^2 \qquad \text{Eq.(8)}$$

The **D90** value for influenza-A virus is therefore equal to 19.3 J/m^2. The D90 value has a high practical interest as it allows the designer to quickly evaluate the required UV dosage to reach a desired disinfection level. For example, providing a UV dose of twice the D90 will result in a disinfection level of 99%. Delivering three times the D90 dose will result in 99.9% disinfection rate, and so on. It can be easily demonstrated mathematically that the number of 9s, also called the disinfection LOG value, is simply equal to the delivered UV dose divided by the D90 value. Extensive compilations of published k values can be found in several places in the literature and in the appendix of Kowalski's UVGI Handbook [(13)].

It is commonly observed in most methods of disinfection that a tiny fraction of the microbial population exhibits a higher level of resistance, and the same is true in UV disinfection (Chick et al. 1963). When the exposure dose is sufficient to cause several logs of reduction (i.e. 99% disinfection or higher) in the microbial population, the surviving population is often an order of magnitude more resistant to UV. That is, the UV rate constant for the resistant population may be ten times lower than for the first stage. This effect will, of course, only be apparent if the disinfection rate is very high, sometime as much as six logs of disinfection. In effect, most microbial populations behave as if two separate populations were present – one relatively susceptible and one relatively resistant. The first stage of decay (fast decay) will then be defined by the susceptible portion of the population and the second stage of decay (slow decay) will be defined by the resistant population. Since the resistant fraction is often on the order of about 1% or less, the second stage only becomes manifest at about the D99 value or higher. An alternate model for two stage curves (or tailing effects) has been proposed by Hiatt (1964).

Sanuvox Technologies Inc.
146 Barr.
St-Laurent, Qc.,
H4T 1Y4

p. 1.888.726.8869
f. 1.888.582.6475
e. info@sanuvox.com

5-Simulation results summary

The simulations were conducted for air flows ranging from 100 CFM to 500 CFM by increment of 50 CFM. The table below is a summary of the simulation results for common airborne microorganisms including SARS-CoV-2 virus.

Effectiv-HVAC-8"Diffuser-Disinfection Simulation of SANUVOX Single LMPHGJ105 UVC-254nm

SANUVOX	500 CFM	450 CFM	400 CFM	350 CFM	300 CFM	250 CFM	200 CFM	150 CFM	100 CFM
Bio-contaminants list									
Mycobacterium tuberculosis	100,00%	100,00%	100,00%	100,00%	100,00%	100,00%	100,00%	100,00%	100,00%
Legionella pneumophila	99,99%	100,00%	100,00%	100,00%	100,00%	100,00%	100,00%	100,00%	100,00%
Candida auris	99,99%	100,00%	100,00%	100,00%	100,00%	100,00%	100,00%	100,00%	100,00%
Coronavirus (SARS-CoV-1)	99,97%	99,99%	100,00%	100,00%	100,00%	100,00%	100,00%	100,00%	100,00%
Proteus mirabilis	99,79%	99,90%	99,96%	99,99%	100,00%	100,00%	100,00%	100,00%	100,00%
Mycoplasma pneumoniae	99,75%	99,87%	99,94%	99,98%	100,00%	100,00%	100,00%	100,00%	100,00%
Listeria monocytogenes	99,28%	99,58%	99,79%	99,91%	99,97%	99,99%	100,00%	100,00%	100,00%
Salmonella	99,12%	99,48%	99,73%	99,88%	99,96%	99,99%	100,00%	100,00%	100,00%
Aeromonas	98,70%	99,20%	99,56%	99,80%	99,93%	99,98%	100,00%	100,00%	100,00%
Covid19 (SARS-CoV-2)	98,17%	98,83%	99,33%	99,67%	99,87%	99,97%	100,00%	100,00%	100,00%
Ricksettsia prowazekii	97,69%	98,48%	99,10%	99,54%	99,81%	99,95%	99,99%	100,00%	100,00%
Staphilococcus epidermis	96,88%	97,88%	98,69%	99,30%	99,69%	99,90%	99,98%	100,00%	100,00%
E. Coli	96,46%	97,56%	98,46%	99,15%	99,62%	99,87%	99,98%	100,00%	100,00%
Yersinia enterocolitica	96,26%	97,40%	98,35%	99,08%	99,58%	99,86%	99,97%	100,00%	100,00%
Coxiella burnetii	96,26%	97,40%	98,35%	99,08%	99,58%	99,86%	99,97%	100,00%	100,00%
Lactobacillus reuteri	96,26%	97,40%	98,35%	99,08%	99,58%	99,86%	99,97%	100,00%	100,00%
Vaccinia virus	96,22%	97,37%	98,33%	99,07%	99,57%	99,86%	99,97%	100,00%	100,00%
smallpox	96,20%	97,36%	98,32%	99,06%	99,57%	99,86%	99,97%	100,00%	100,00%
Newcastle disease	95,41%	96,74%	97,88%	98,78%	99,41%	99,79%	99,95%	100,00%	100,00%
Acinetobacter baumanii	93,54%	95,23%	96,74%	98,00%	98,96%	99,58%	99,89%	99,99%	100,00%
influenza A virus	92,17%	94,10%	95,85%	97,37%	98,57%	99,39%	99,83%	99,98%	100,00%
MRSA	91,09%	93,19%	95,13%	96,84%	98,22%	99,21%	99,76%	99,97%	100,00%
Coxsachievirus	90,70%	92,86%	94,87%	96,64%	98,09%	99,14%	99,74%	99,96%	100,00%
Avian Influenza virus	89,65%	91,96%	94,13%	96,09%	97,72%	98,93%	99,66%	99,95%	100,00%
Measle virus	89,45%	91,78%	93,99%	95,98%	97,64%	98,89%	99,64%	99,94%	100,00%
Pseudomonas aeruginosa	89,36%	91,71%	93,92%	95,93%	97,61%	98,87%	99,63%	99,94%	100,00%
Serratia marcescens	86,91%	89,55%	92,12%	94,52%	96,62%	98,29%	99,38%	99,89%	100,00%
Parvovirus H-1	86,04%	88,78%	91,47%	93,99%	96,24%	98,05%	99,27%	99,86%	99,99%
Proteus vulgaris/mirabilis	80,65%	83,88%	87,17%	90,43%	93,53%	96,26%	98,35%	99,58%	99,97%
Corynebacterium diphteriae	77,69%	81,12%	84,67%	88,27%	91,79%	95,02%	97,65%	99,33%	99,94%
Ustilago zeae	75,54%	79,08%	82,80%	86,62%	90,43%	94,02%	97,04%	99,08%	99,91%
Streptococcus pyogenes	73,25%	76,89%	80,76%	84,79%	88,89%	92,84%	96,30%	98,77%	99,86%
Haemophilus influenza	72,25%	75,93%	79,86%	83,98%	88,19%	92,30%	95,94%	98,61%	99,84%
Yeast	70,82%	74,55%	78,56%	82,79%	87,16%	91,49%	95,40%	98,35%	99,79%
Klebsiella pneumoniae	69,05%	72,83%	76,91%	81,28%	85,84%	90,42%	94,67%	97,99%	99,72%
Neisseria catarrhalis/meningitidis	67,37%	71,19%	75,34%	79,81%	84,53%	89,35%	93,92%	97,61%	99,63%
Clostridium tetani	63,42%	67,28%	71,55%	76,23%	81,29%	86,62%	91,91%	96,50%	99,34%
Vancomycin Resistant Enterococcus	59,21%	63,08%	67,40%	72,22%	77,56%	83,36%	89,37%	94,97%	98,87%
Burkholderia cenocepacia	57,11%	60,96%	65,29%	70,16%	75,61%	81,61%	87,95%	94,05%	98,55%
Adenovirus	56,60%	60,44%	64,77%	69,65%	75,12%	81,16%	87,59%	93,81%	98,46%
Enterobacter cloacae	53,70%	57,49%	61,80%	66,71%	72,29%	78,56%	85,41%	92,32%	97,87%
Reovirus	51,26%	55,00%	59,27%	64,18%	69,81%	76,24%	83,41%	90,89%	97,25%
Norwalk virus	47,82%	51,46%	55,66%	60,52%	66,19%	72,78%	80,34%	88,57%	96,13%
Echovirus	37,42%	40,59%	44,34%	48,80%	54,21%	60,83%	69,01%	79,03%	90,40%
Bacillus Anthacis	30,05%	32,77%	36,03%	39,98%	44,88%	51,07%	59,08%	69,62%	83,25%
Cryptococcus neoformans	30,05%	32,77%	36,03%	39,98%	44,88%	51,07%	59,08%	69,62%	83,25%
Blastomyces dermatidis	29,67%	32,37%	35,60%	39,52%	44,38%	50,54%	58,52%	69,07%	82,80%
Histoplasma capsulatum	29,67%	32,37%	35,60%	39,52%	44,38%	50,54%	58,52%	69,07%	82,80%
Mucor spores	29,67%	32,37%	35,60%	39,52%	44,38%	50,54%	58,52%	69,07%	82,80%
Bacillus subtilis spores	28,23%	30,83%	33,94%	37,74%	42,47%	48,49%	56,36%	66,90%	80,96%
Francisella Tularensis	27,05%	29,57%	32,58%	36,28%	40,89%	46,79%	54,55%	65,06%	79,34%
Fusarium oxysporum	26,21%	28,66%	31,60%	35,22%	39,74%	45,54%	53,22%	63,68%	78,12%
Botrytis cinerea	17,87%	19,65%	21,82%	24,52%	27,97%	32,55%	38,87%	48,12%	62,63%
Rhizopus nigricans	16,83%	18,51%	20,57%	23,14%	26,44%	30,82%	36,91%	45,89%	60,20%
Nocardia asteroides	16,13%	17,75%	19,74%	22,22%	25,41%	29,66%	35,58%	44,37%	58,50%
Penicillium digitatum	14,24%	15,69%	17,47%	19,71%	22,59%	26,46%	31,90%	40,08%	53,62%
Bacillus Cereus spores	11,37%	12,55%	14,00%	15,84%	18,22%	21,45%	26,05%	33,12%	45,31%
Algae blue-green	10,38%	11,46%	12,80%	14,49%	16,69%	19,68%	23,96%	30,60%	42,18%
Streptococcus Pneumoniae	9,99%	11,04%	12,33%	13,96%	16,09%	18,99%	23,14%	29,60%	40,93%

Sanuvox Technologies Inc.
146 Barr.
St-Laurent, Qc.,
H4T 1Y4

p. 1.888.726.8869
f. 1.888.582.6475
e. info@sanuvox.com

6- Conclusions

The use of our 254 nm monochromatic J-shaped UVC source LMPHGJ105 inside the EffectivHVAC special diffuser can effectively insure a significant disinfection rate in a single pass for a wide range of common airborne microorganisms including the SARS-CoV-2 virus.