Ultraviolet disinfection for large indoor air supply systems

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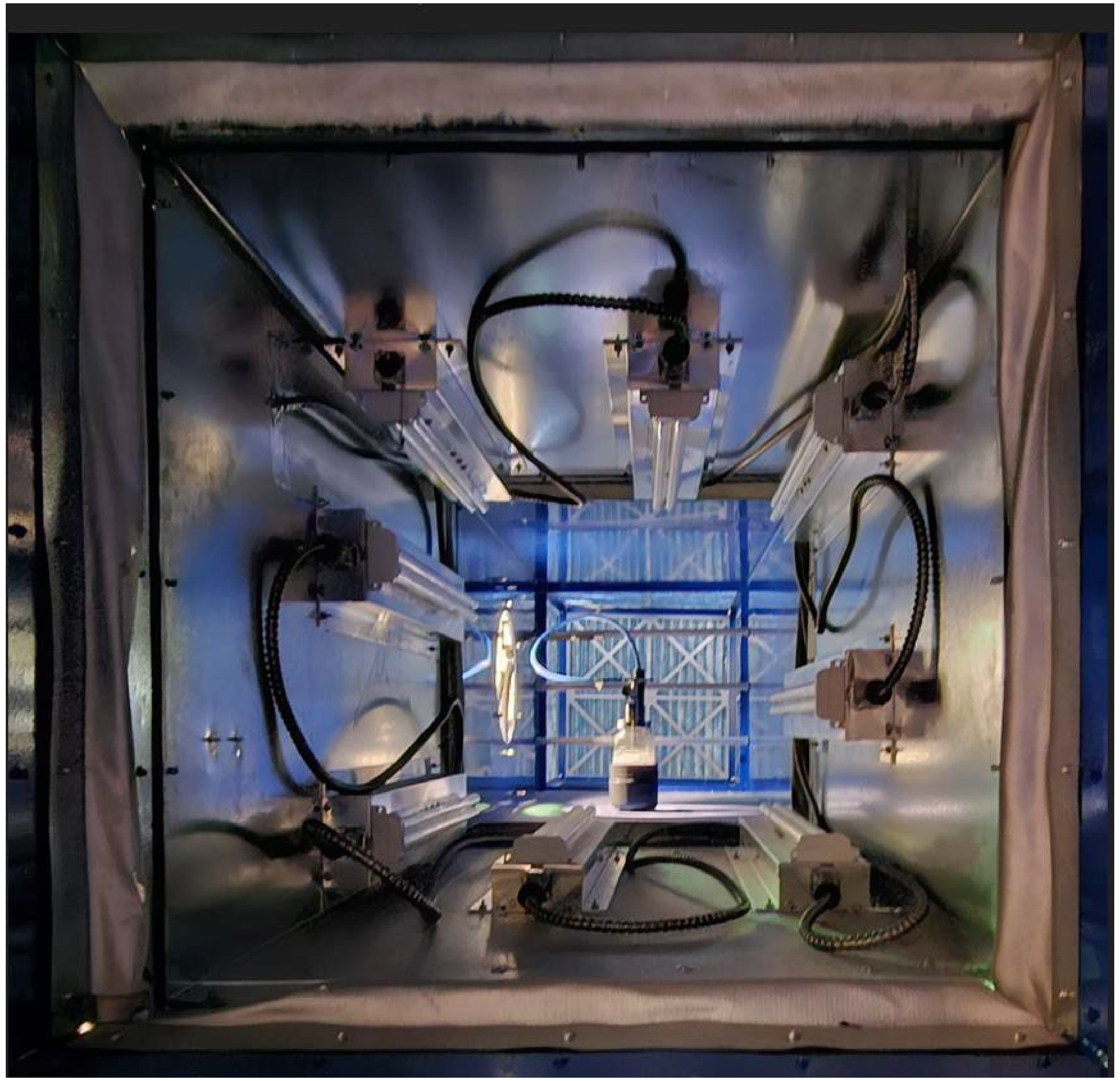


החברה הכלכלית

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

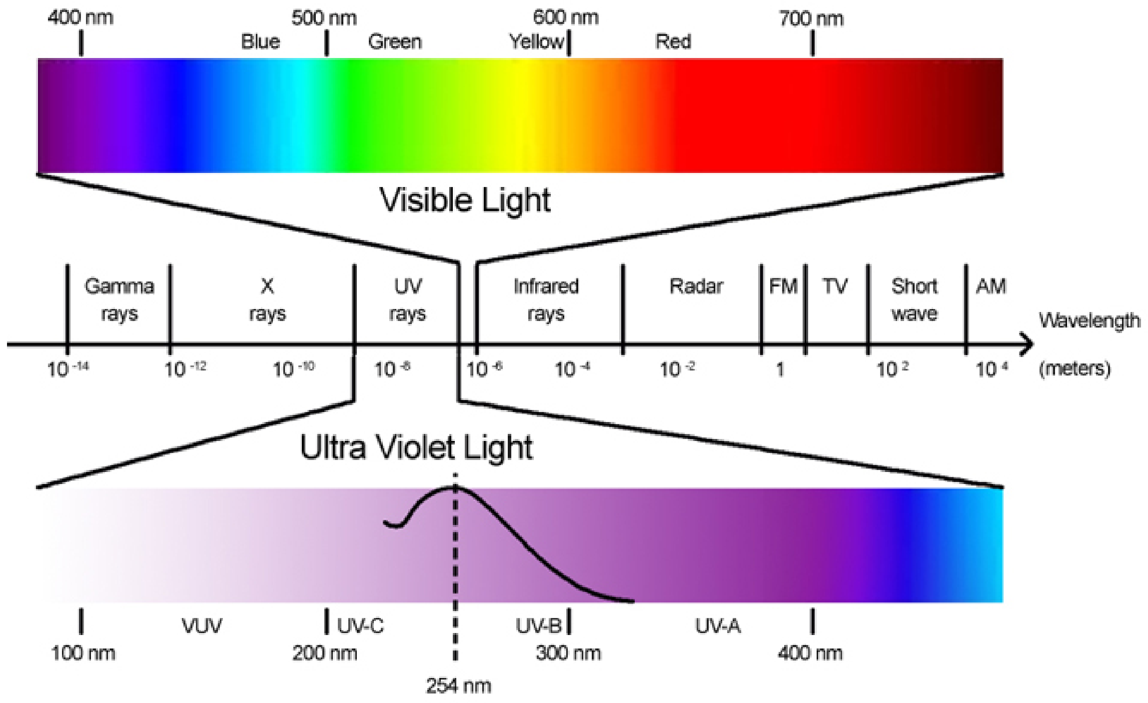
אלקטרה CONSIDER IT DONE

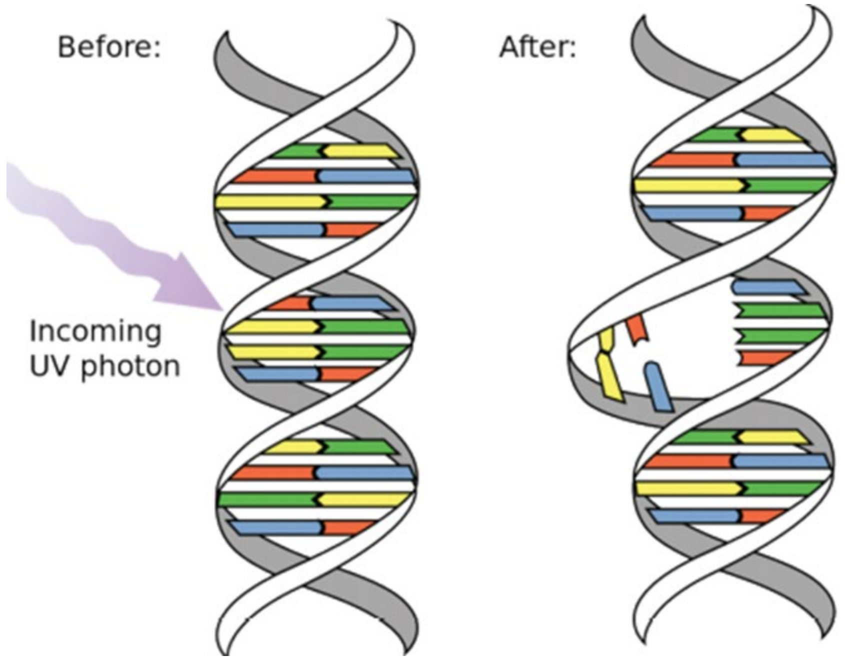
Air Disinfection in Large Indoor Spaces

- Challenge: Low ventilation & high recirculation increase pathogen spread in hospitals, theaters, classrooms, gyms.
- Energy-efficient, cost-effective disinfection are needed to reduce airborne transmission in large ventilated indoor spaces
- Effectiveness of ultraviolet (UV) light for disinfection of air alone, or in combination with particulate air filters is well established

UV disinfection

- UV between 200-400 nanometers (nm)
- Wavelengths between 200 and 300 nm are germicidal (UVC/UVB)
- Photons absorbed by DNA (or RNA)
- A dimer formed - interaction between two molecules
- Inhibits replication
- Capable of inactivating bacteria, viruses and protozoa.
- Most UVGI lamps create UV-C energy with an electrical discharge through a low-pressure gas (including mercury vapor)
- Lamps are enclosed in a soft glass or quartz tube, similar to fluorescent lamps.
- LP lamps emitted at a wavelength of 253.7 nm





https://pubs.acs.org/doi/10.1021/acsphotonics.2c00041

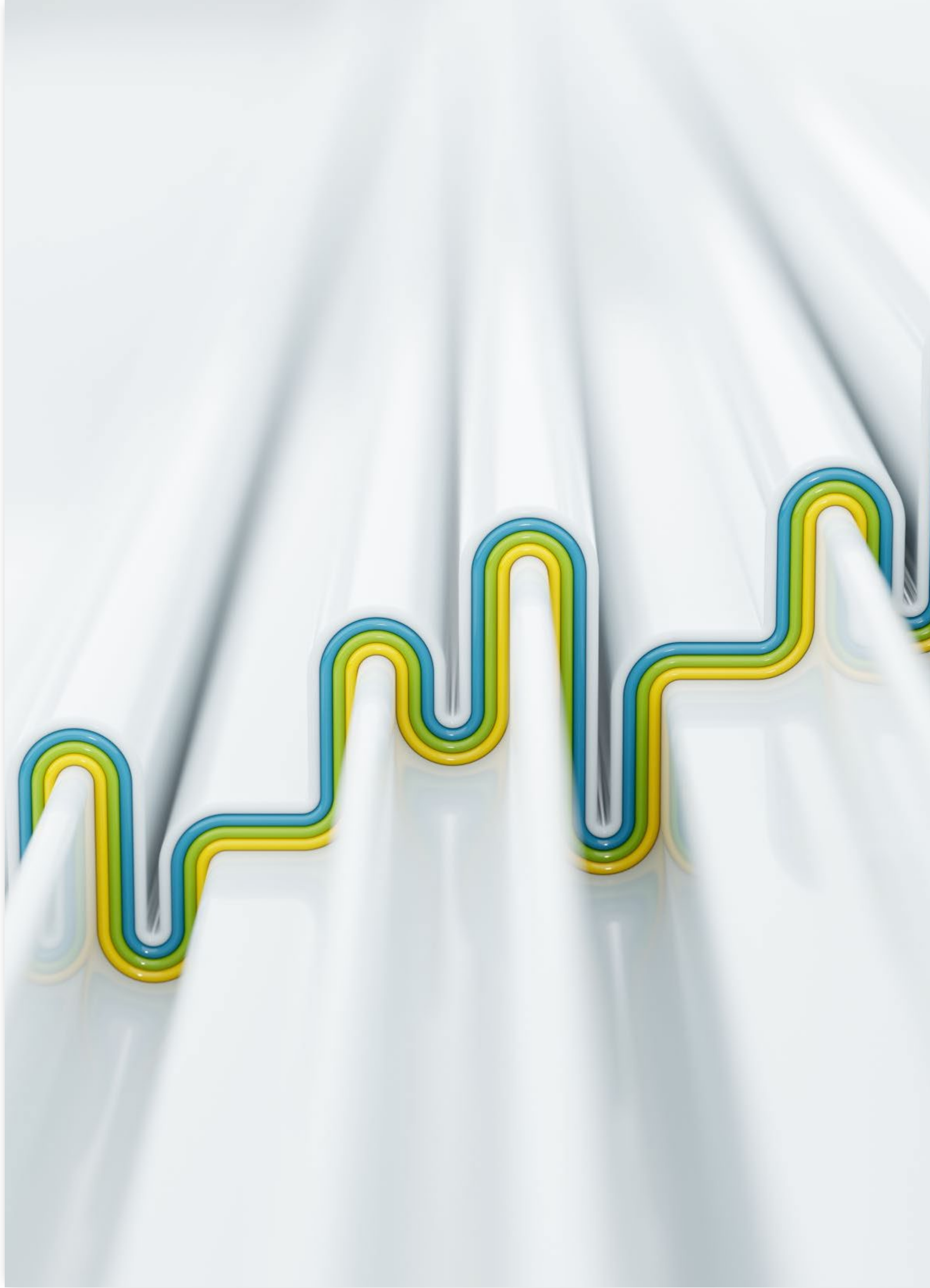
Challenges in In-Duct UV Air Disinfection

Microorganisms present in the air pass through the disinfection zone for a short exposure time

High airflow rates and large HVAC ducts lead to uneven disinfection:

- Difficult to control aerosol residence time and measure inactivation reliably.
- Lack of accurate airflow and UV mapping data.

Designing a 1:1 experimental system can answer real challenges and simulations of realistic in-duct UV systems

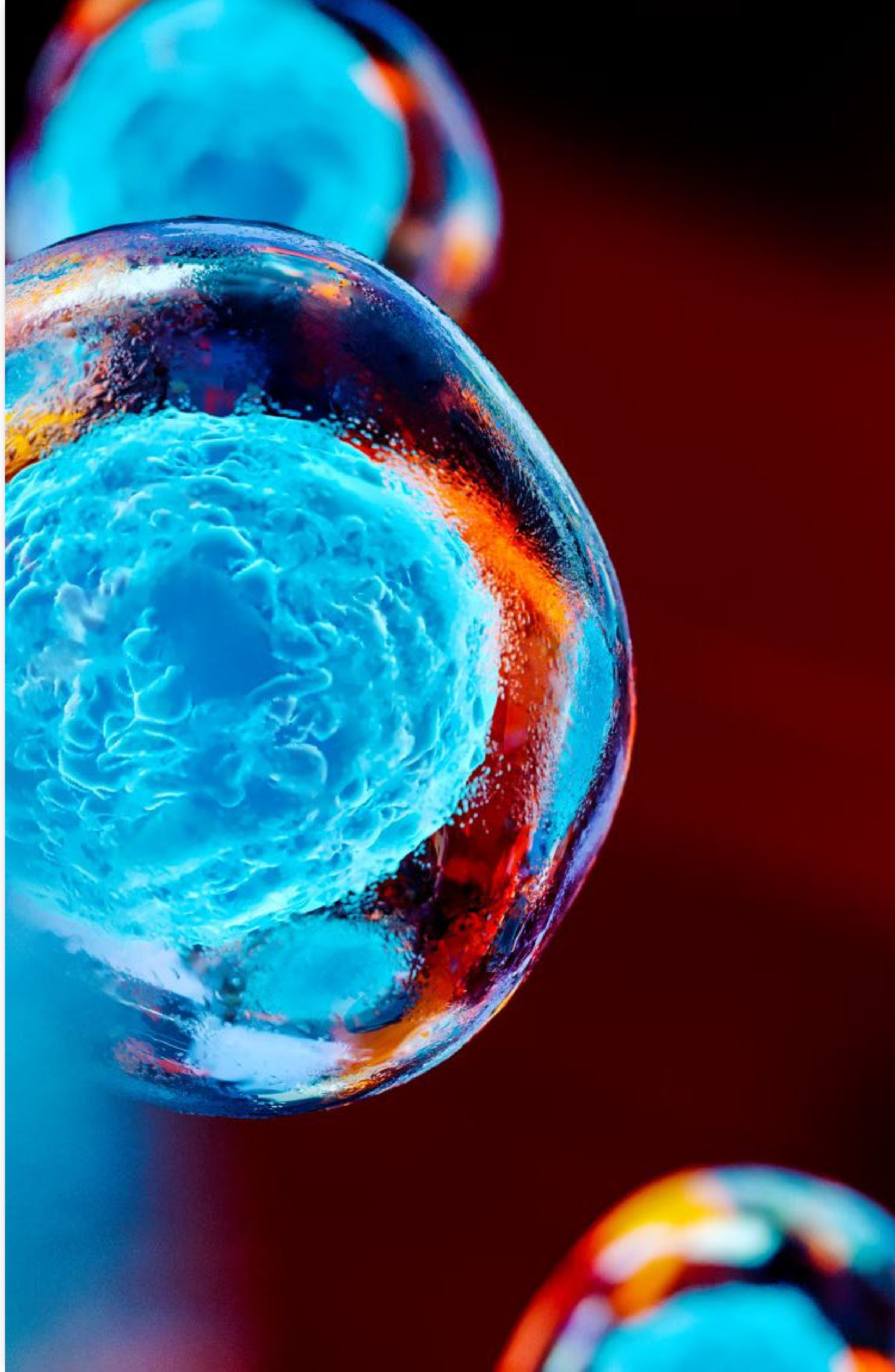


Challenges in Optimizing UV Disinfection in HVAC Systems

- Limited understanding of airflow effects, UV radiation mapping, surface reflectivity, temperature, and humidity impacts - **leads to inaccurate predictions and simulations**.
- To optimize log_{10}-reduction we need to adjust UV dose—**reducing/increasing** the dose for the **over/under-exposed** ones

Open Questions:

- How can we achieve cost-effective, energy-efficient UV disinfection **at realistic airflow rates**?
- How to position the lamp banks - parallel or perpendicular to the airflow?



Air UV disinfection requirements

High UV doses to inactivate microorganisms:

- A conservative minimum target UV dose of 1,500 μJ/cm^2 for 99% inactivation of SARS-CoV-2
- 500 fpm moving airstream (680 m^{3}hr)
- Minimum irradiance zone of two feet (0.6 meter)
- Minimum UV exposure time of 0.25 second

Should always be coupled with mechanical filtration

- MERV 8 filter for dust control
- Highest practical MERV filter recommended that does not compromise system performance

Filtration / Disinfection

Guidelines for evaluating UV dose in In-duct UV devices

EPA United States Environmental Protection Agency

TECHNOLOGY EVALUATION REPORT

Biological Inactivation Efficiency by HVAC In-Duct Ultraviolet Light Systems

American Ultraviolet Corporation ACP-24/HO-4

Office of Research and Development
National Homeland Security
Research Center

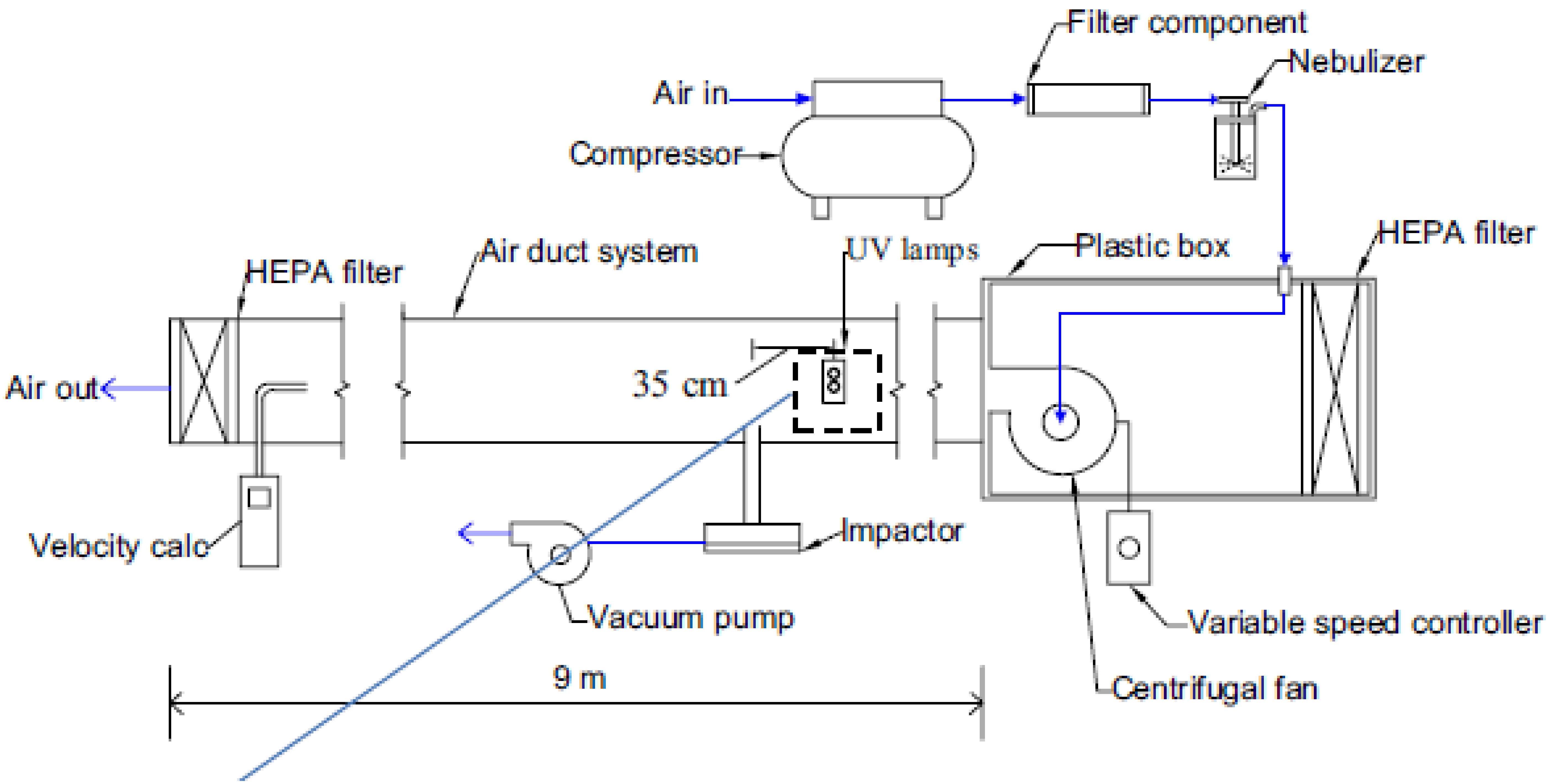
INTERNATIONAL STANDARD

ISO 15714

First edition
2019-07

Method of evaluating the UV dose to airborne microorganisms transiting in-duct ultraviolet germicidal irradiation devices

Méthode d'évaluation de la dose d'UV pour les microorganismes en suspension dans l'air transitant par des dispositifs d'irradiation germicide aux ultraviolets raccordés



Disinfection efficacy of ultraviolet germicidal irradiation on airborne bacteria in ventilation ducts

Yi Yang[1,2] | Huihui Zhang[3] | Sunday Segbenu Nunayon[3] | Vincent Chan[4] | Alvin CK Lai[3]

Research goal

- Objective: Address key challenges in pathogen mitigation within large HVAC systems
- Approach: Construct a 1:1 simulated air duct lab at Tel Aviv University
- Focus: Adapt UV irradiation for in-duct disinfection through combined computational and experimental methods.

Parameters needed to design UV inactivation experiments

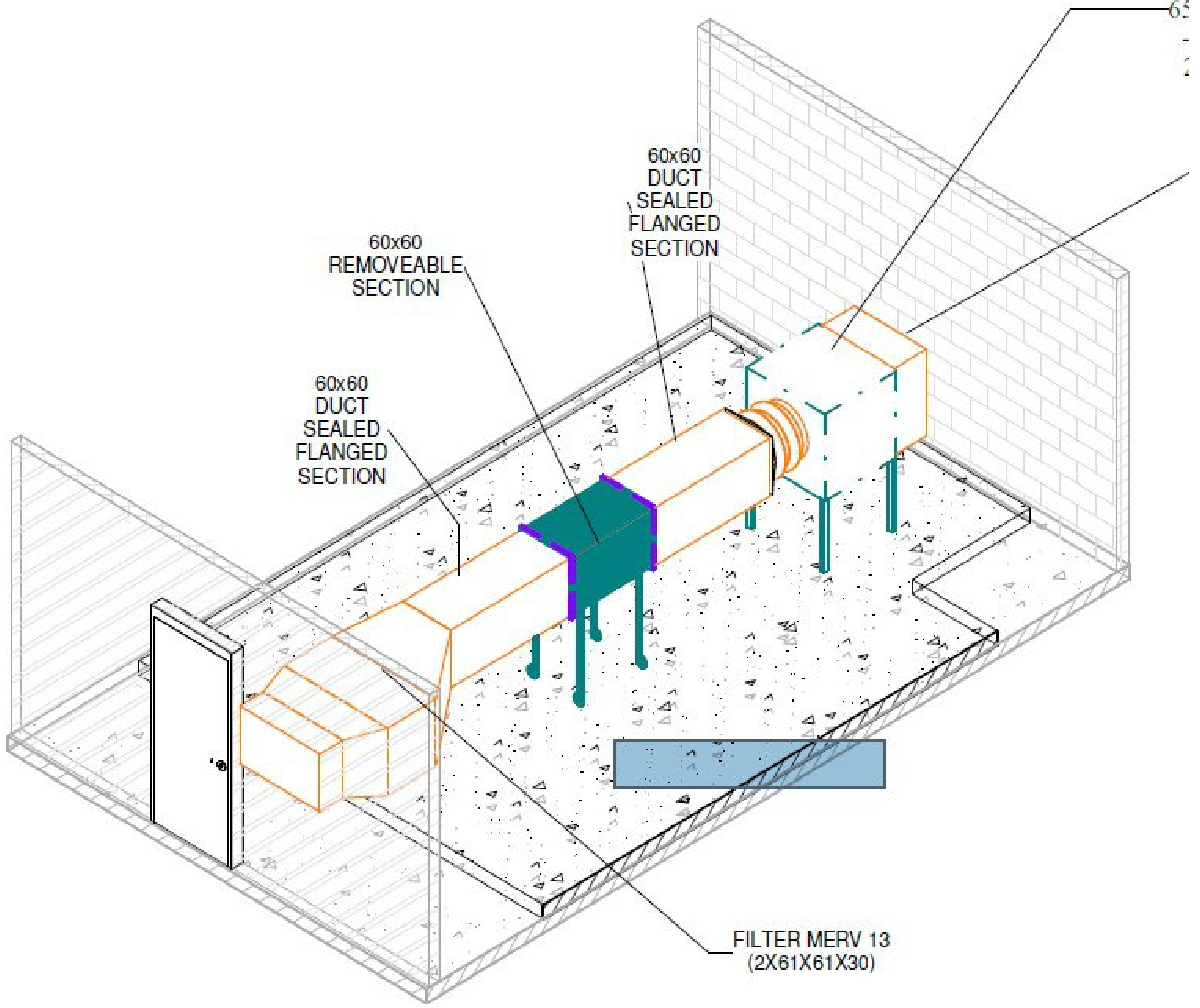
$$\text{UV dose} = \frac{P}{Q} \times L$$

Where:

- P: UV output (Watts)
- Q: Airflow rate (m^3/sec)
- L: UV exposure length (meters)
- A: Cross-sectional area of the duct (m^2)

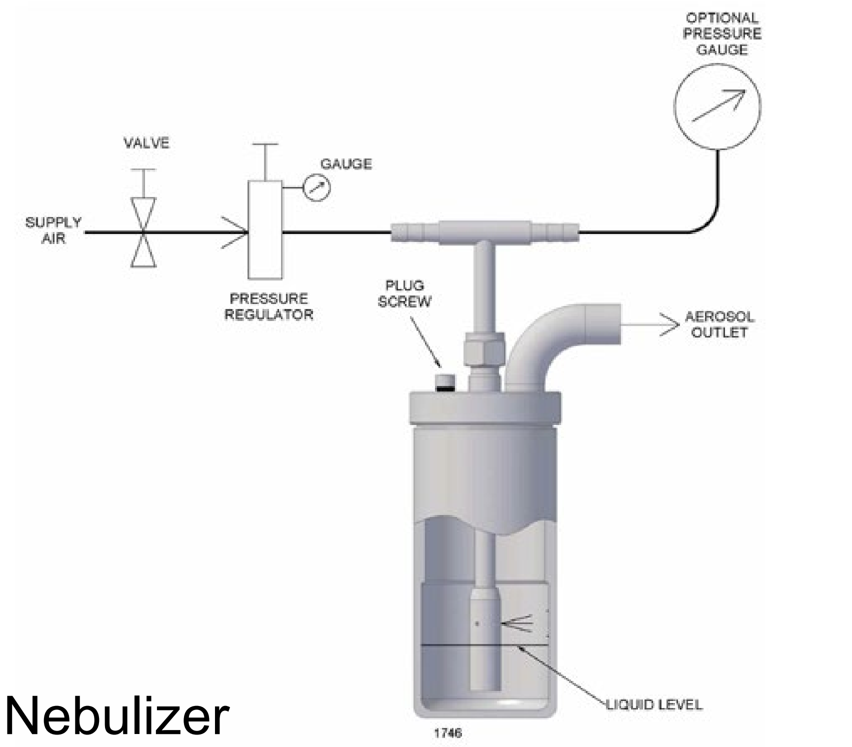
- **Air flow rate**
- **Dimensions:** Height, Width, and Length of duct
- **% reflectivity** of inner surfaces
- **Irradiance:** for example - μW/cm^2 @ 1 meter
- **Lamp UV output power** (W), UV output, lamp length and diameter, lifetime, ozone-free, voltage, Amps
- **Lamp fixtures mounting**, easy installation, replacement, check lamp output
- In-line **operation** and lamp status indicator
- **Position coordinates** of each lamp (xi, yi, zi)
- **Target microorganism** rate constant k in m^2/J

The Air-UV lab



- Air channel: 0.60 m height x 0.6 m width x 1 m length
- The system includes a suction filter, blower, Aerosol generator, UV disinfection channel zone, air sampler
- Flow velocity 4.5 m/s
- Optical power UVC lamps - 254nm: lamps 95 W in a rack

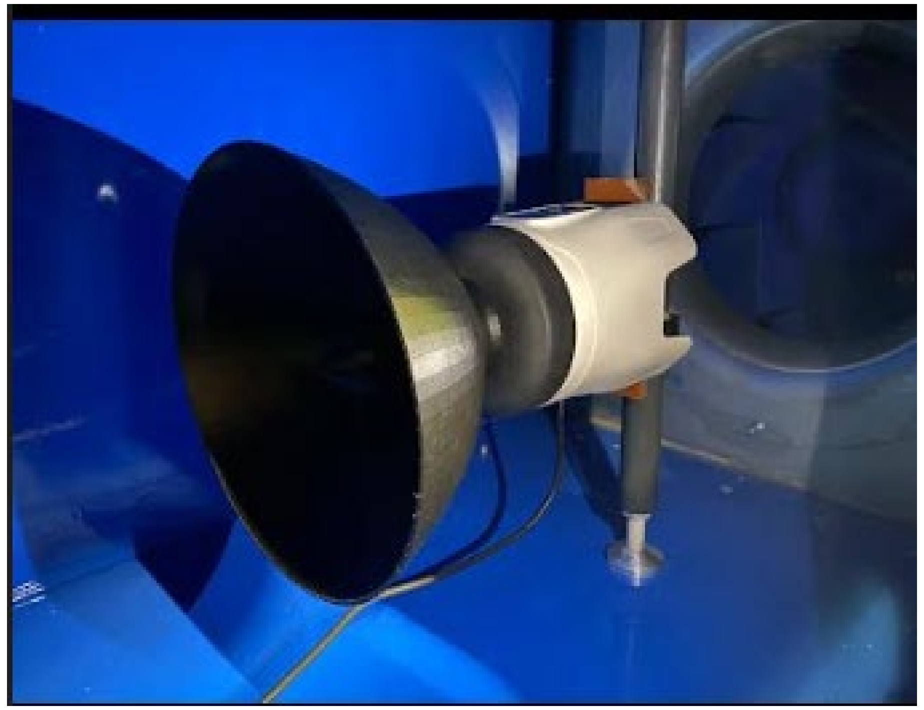
System set up



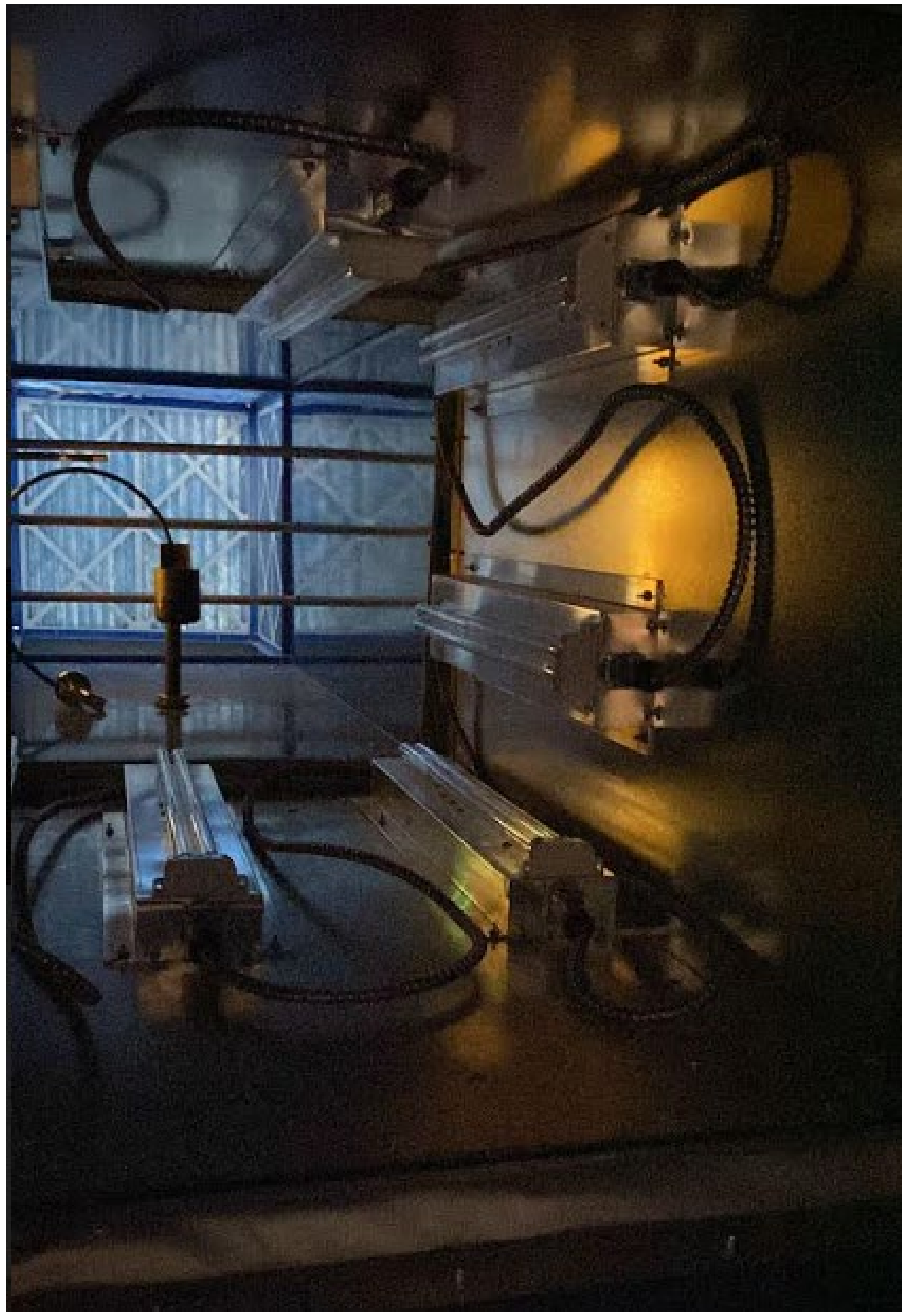
System

Nebulizer

Sampler



Lamp position

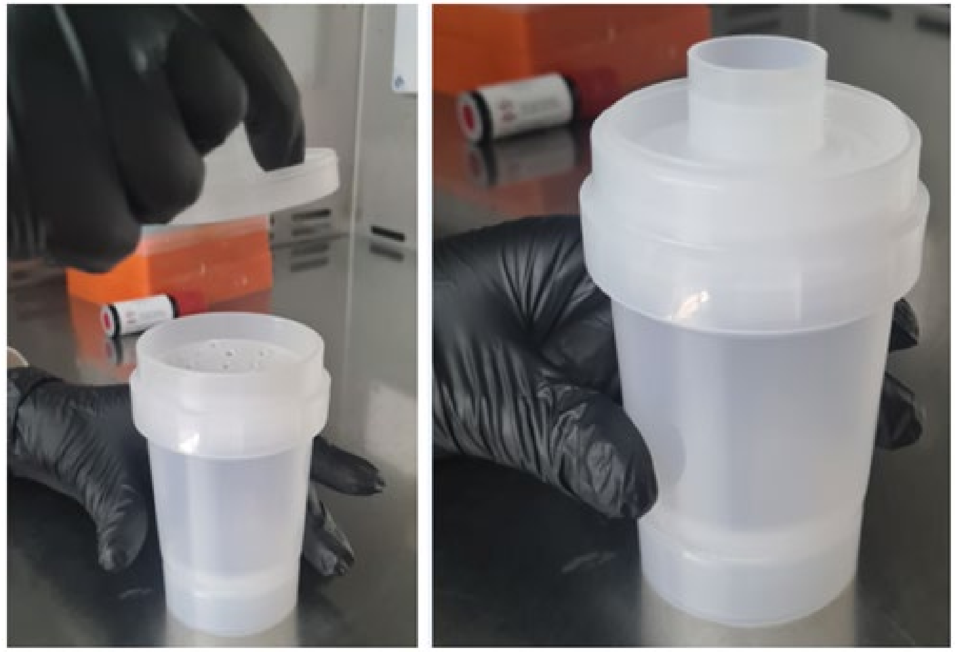


Examining the nebulizer

Aerosols

- Small aerosols (<10 µm), are airborne and infectious for extended periods (minutes, hours, or days) and travel longer distances
- Large droplets (100 µm diameter) may shrink by evaporation before they settle, and become an aerosol (<10 µm)
- Role of indoor air management is critical in providing a line of defense
- The MS2 bacteriophage is used as a surrogate for hospital air aerosols because it is safe, highly resistant to UV, similar in size to many human viruses
- **MS2 serves as a worst-case scenario** for testing air disinfection systems.

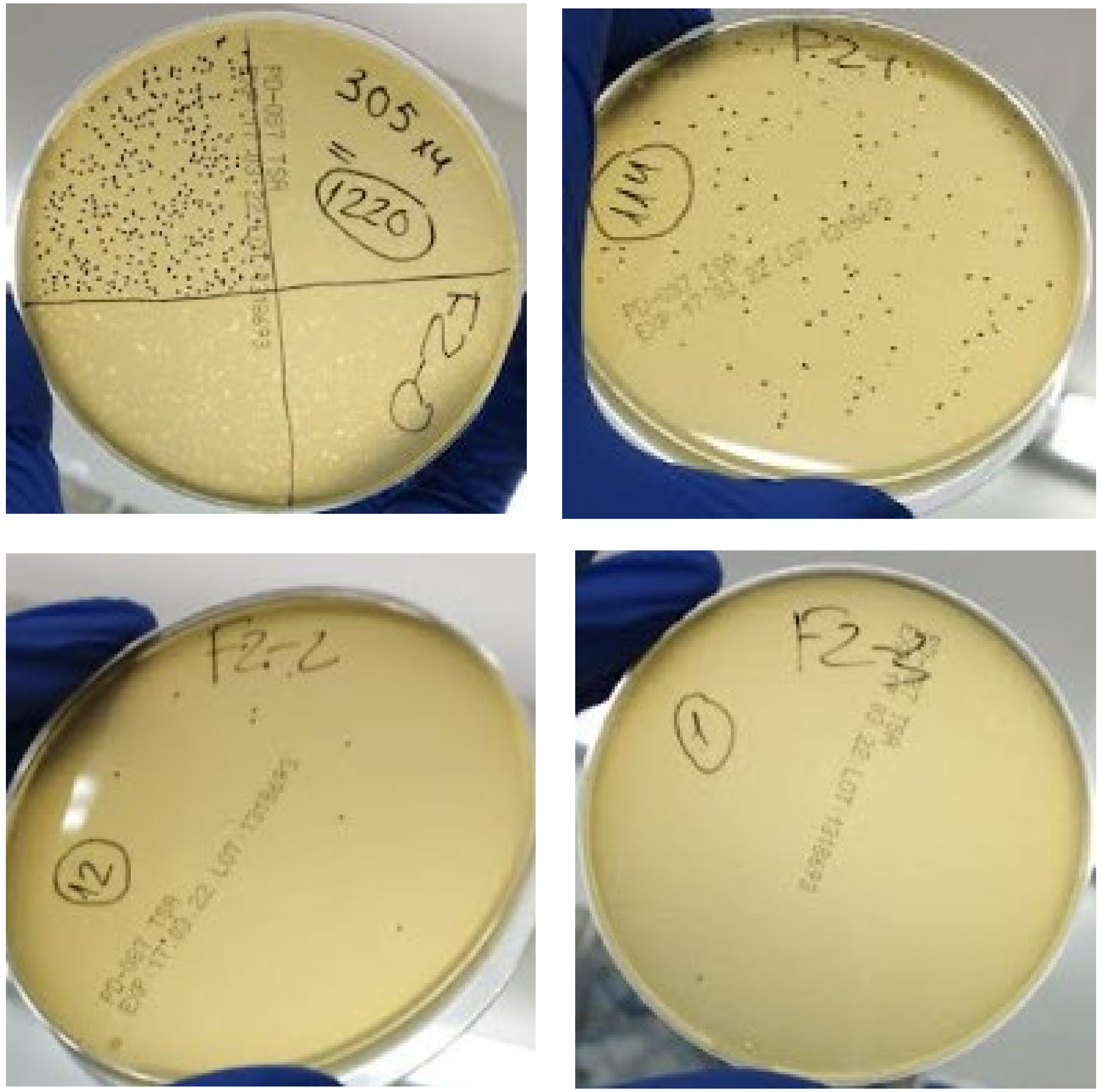
MS2 recovery from air sampler (Bobcat) filter

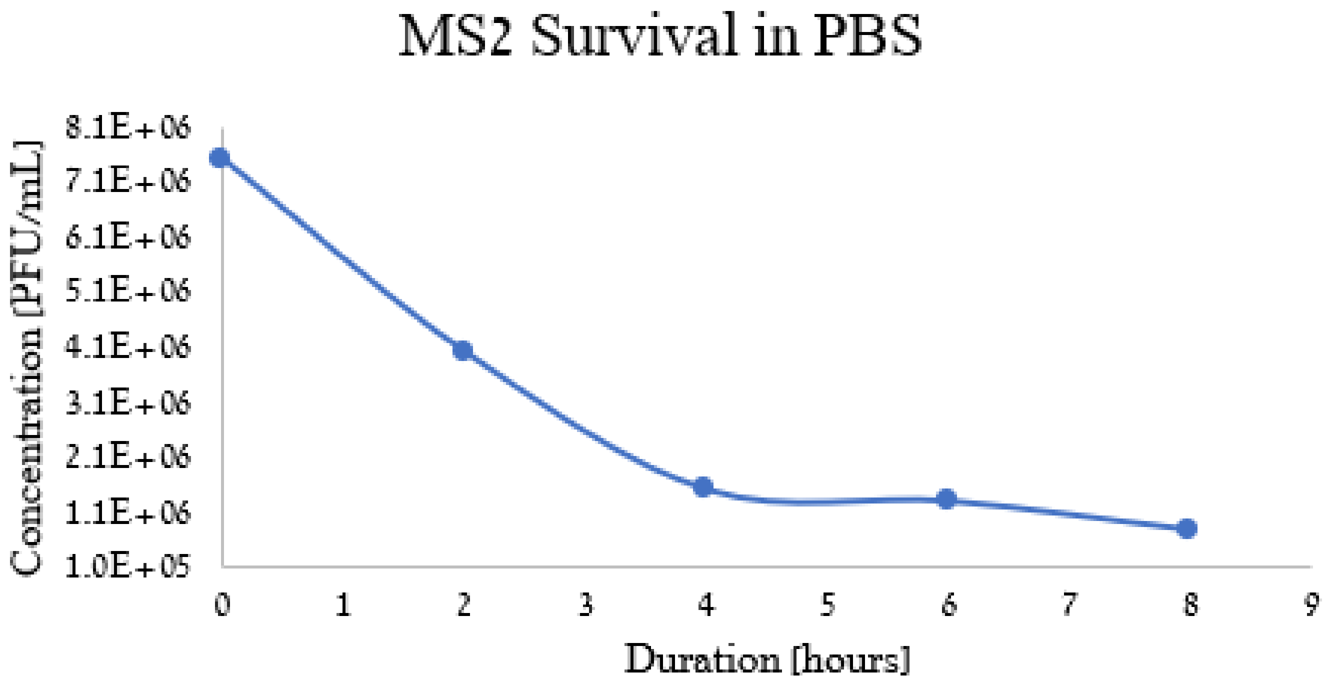


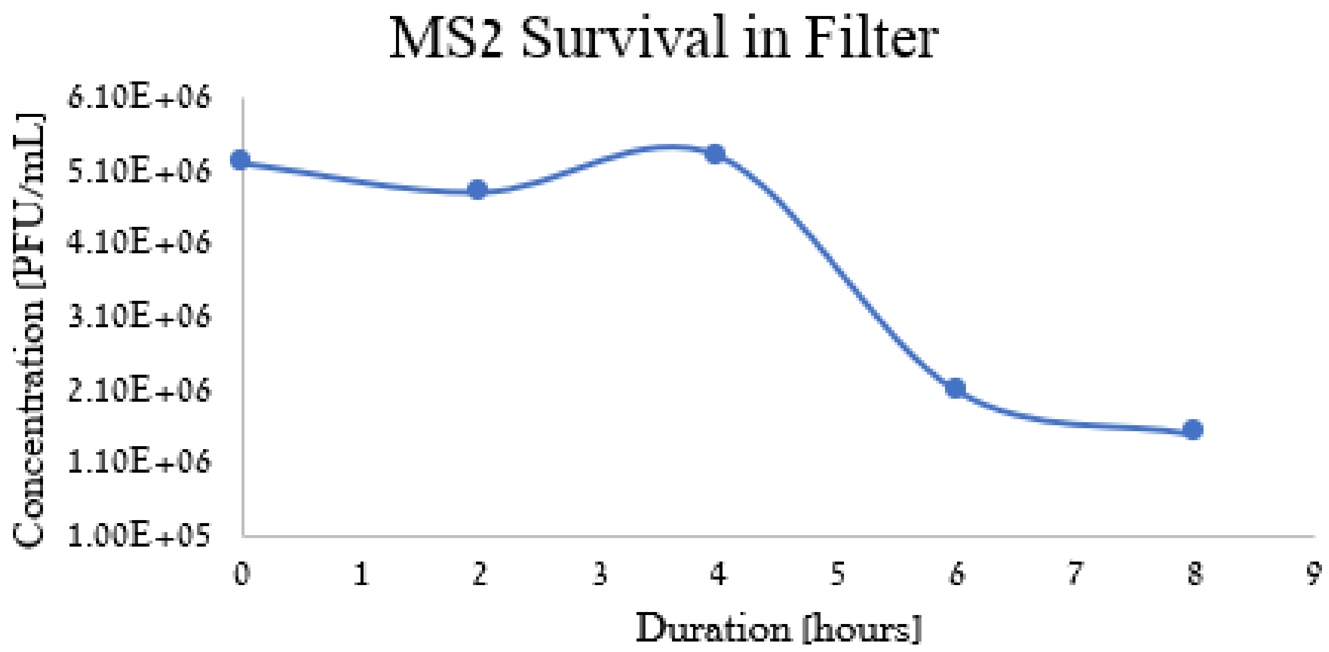
Tests conducted: MS2 extraction validation and survival on filter for 8 hrs

- MS2 phage stock at a concentration of ~10^8 PFU/mL placed in the nebulizer
- A sterile new filter was placed in the Bobcat
- At the end of the experiment, the filter was attached to the extraction cup and lid covered
- The virus extracted using the extraction foam (PBS)

Example of MS2 enumeration

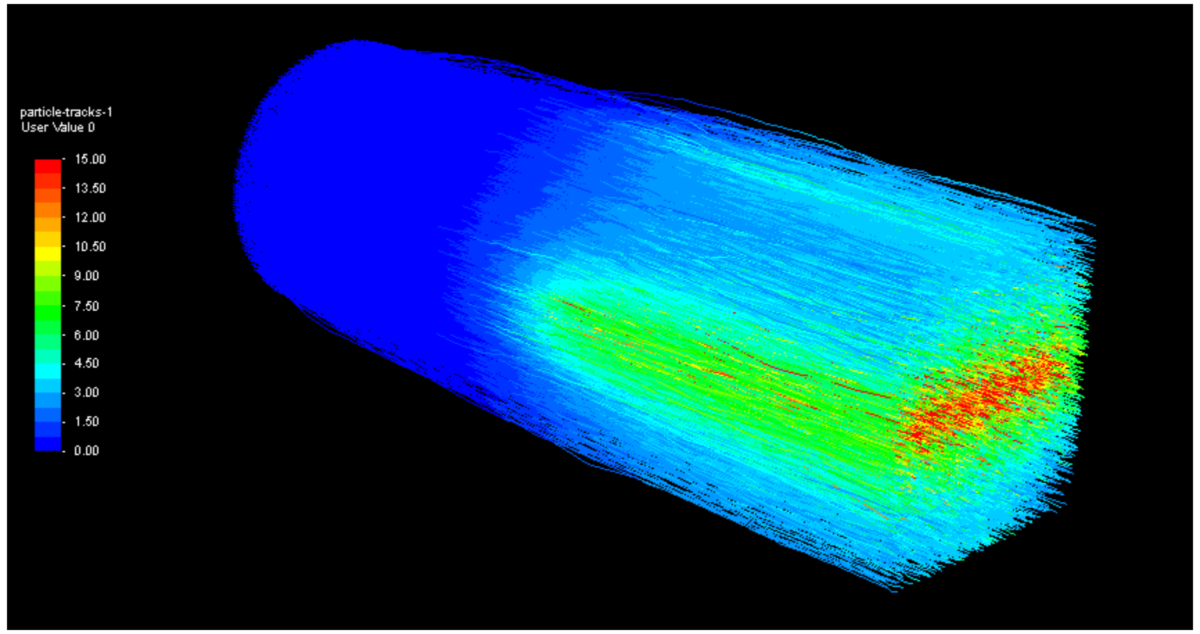


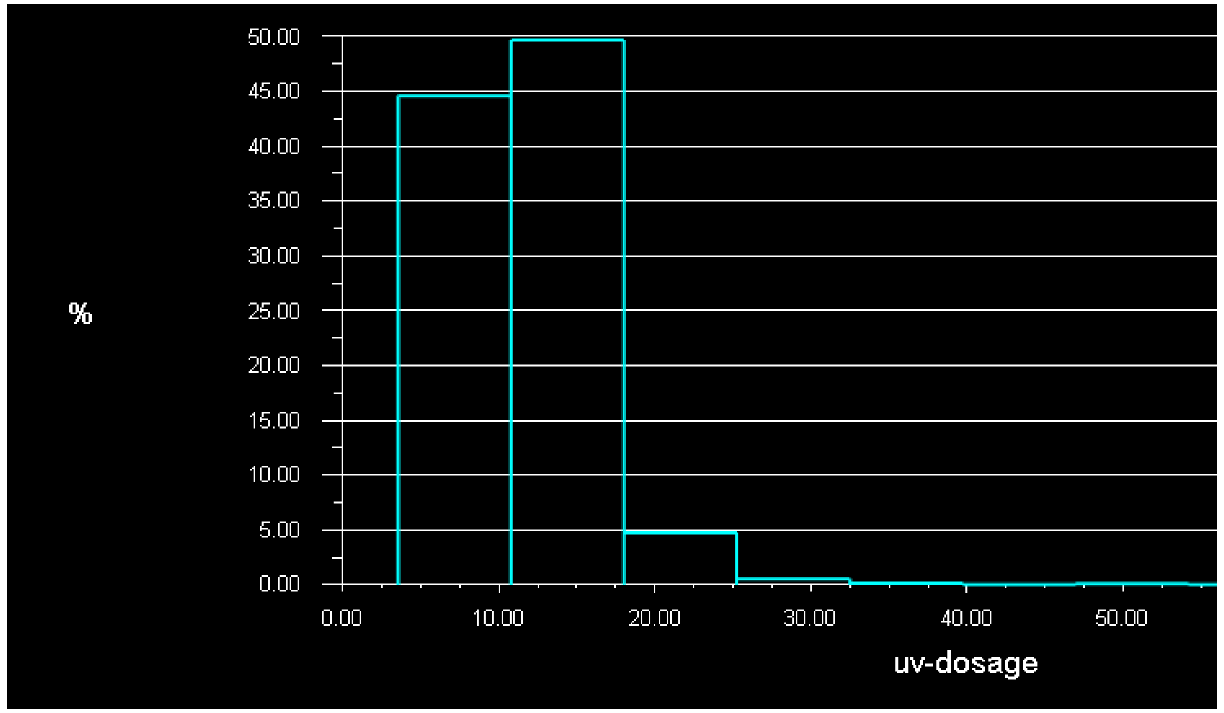




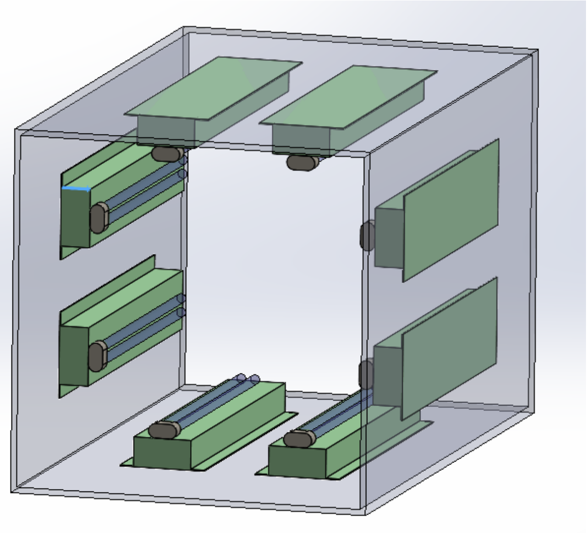
Simulation

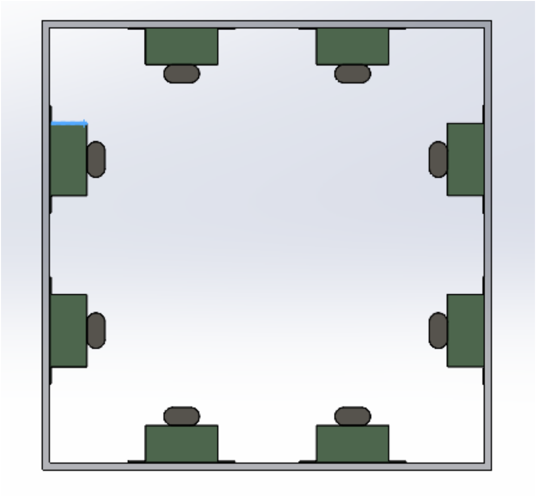
- Simulation integrating optics, fluid mechanics, including particle movement, and the impact of environmental conditions.
- **Determining the most practical combination** of lamps/light sources/wavelengths for the specific requirements using the simulation output that includes customization of UV lamp arrangements and combinations.





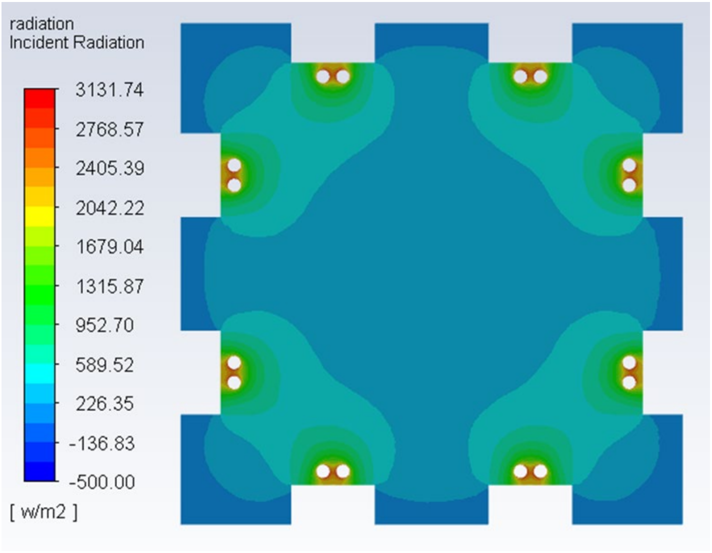
Configuration





Geometry:

- Air channel: 0.60 m height x 0.6 m width x 1 m length
- Entire system includes suction filter, blower, Aerosol generator, UV disinfection channel zone, air sampler
- Flow velocity 4.5 m/s (~ 6000 m^3/h)



Power

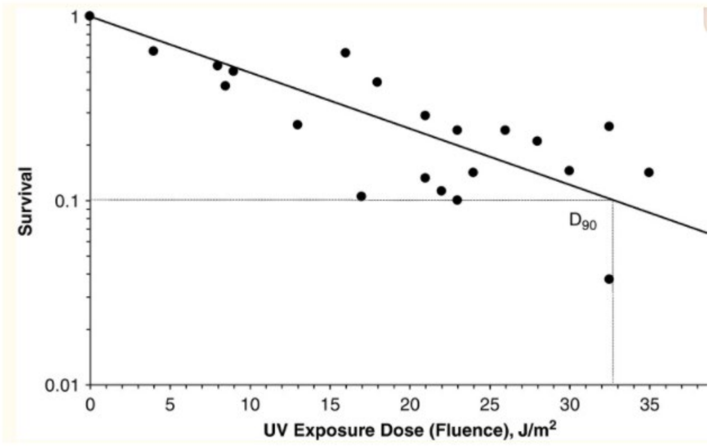
- Optical power UVC lamps - 254nm: lamps 95 W in a rack

Assumptions for simulation

UVT- 97% -α=−ln(UVT/100)×100=3.05[1/m]−$absorption\ coefficient$

Refraction index =1.0003

1 log inactivation=90%



Walls aluminum

- Case 1 ~ 20% reflection
- Case 2 ~ 73% reflection

$$\%\ inactivation\ = \left(1 - e^{-k*D}\right) * 100$$

D- UV Dose $\left[\frac{J}{m^2}\right]$

k= UV Constant Rate $\left[\frac{m^2}{J}\right]$

k constant given for MS2 – Thesis vs. EPA :

$For\ RH\ 32-50\ \%\qquad k = 0.038\left[\frac{m^2}{J}\right] \rightarrow required\ at\ least\ UV\ Dose\ of\ 60.7\frac{J}{m^2}$

$For\ RH\ 74-85\ \%\qquad k = 0.043\left[\frac{m^2}{J}\right] \rightarrow required\ at\ least\ UV\ Dose\ of\ 53.7\frac{J}{m^2}$

Target UV dose at 1 m plane should possible be 2 - 16 mJ / cm²

Temperature and humidity

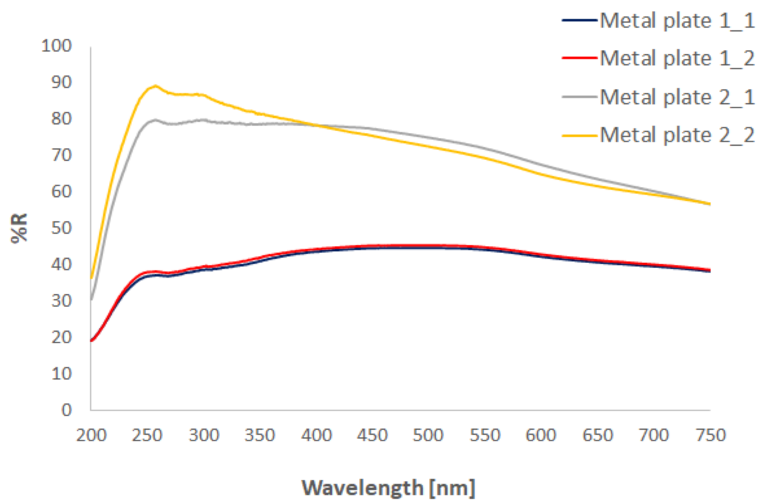
Injected 1000 Particles

Model virus: MS2

MS2 Virus size 25 nm

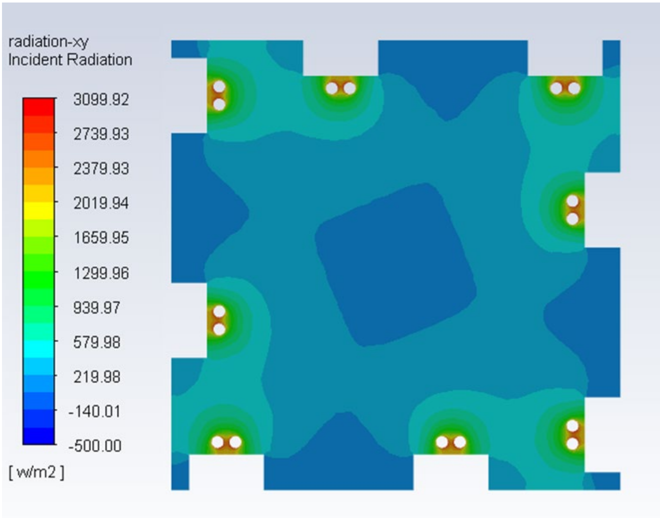
Density of 1350 [kg/m³]

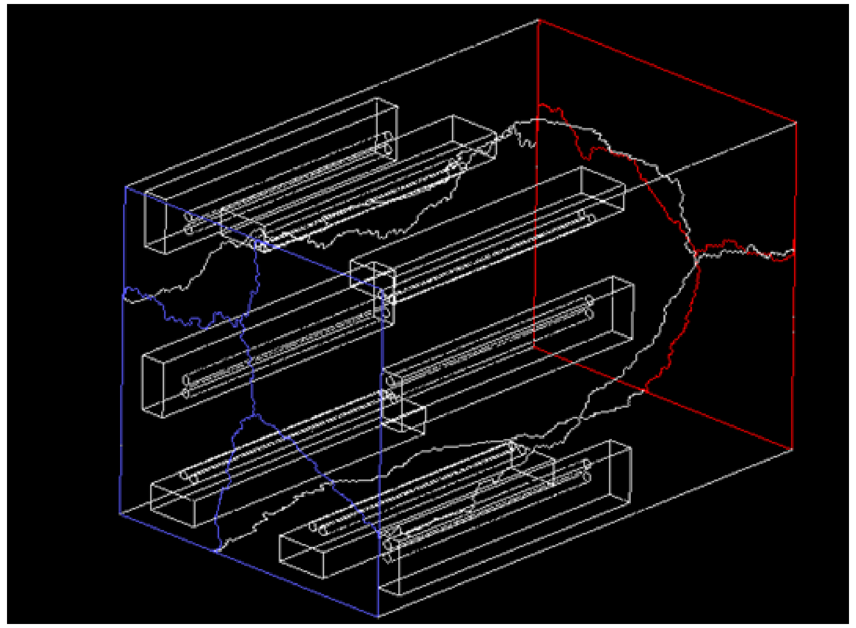
Disinfection target 90% to 99.9%

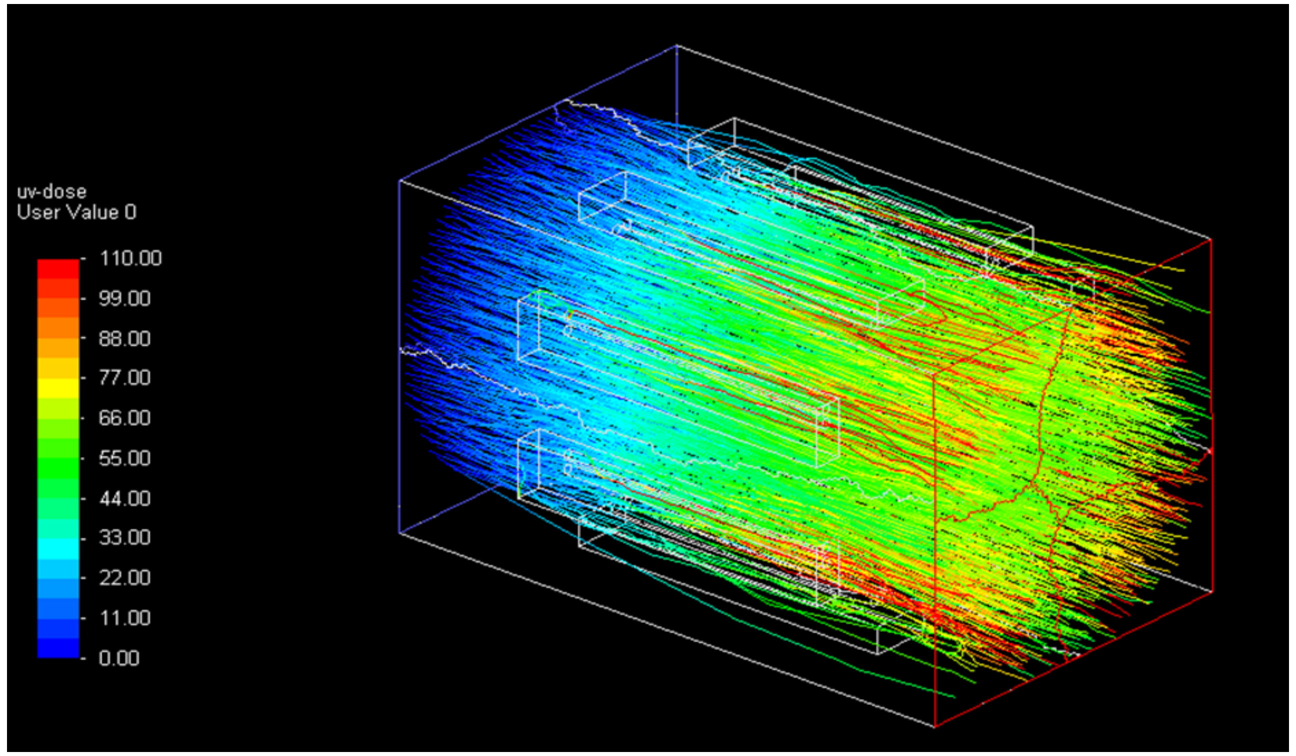


[1]:https://www.researchgate.net/publication/276649143_Computational_fluid_dynamics_analysis_to_assess_performance_variability_of_in-duct_UV-C_systems
[2]: Biological Inactivation Efficiency by HVAC In-Duct Ultraviolet Light System
https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=459254&Lab=NHSRC

CFD results



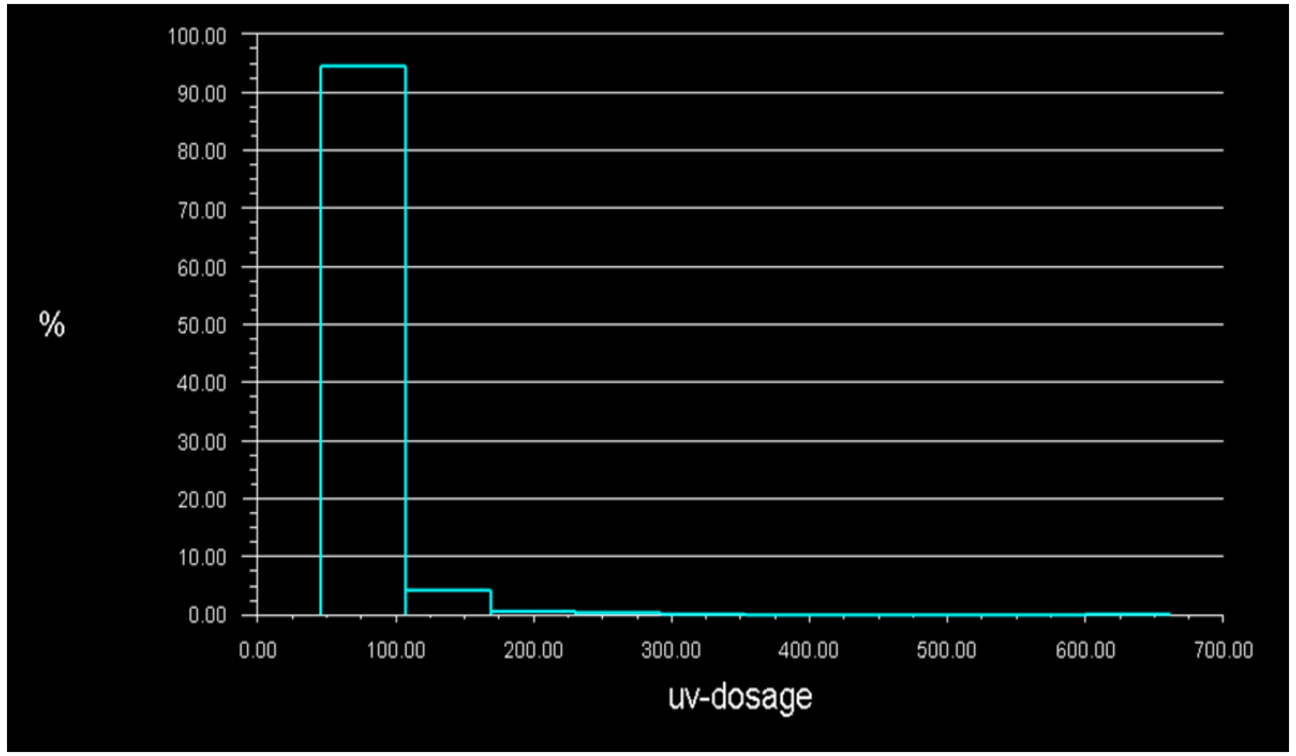




From ref. | CFD Results | Below the required 99%

8 lamps

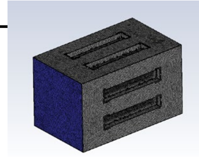
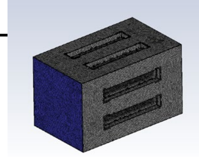
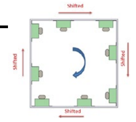
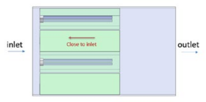
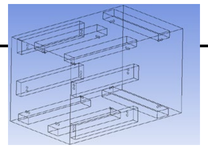
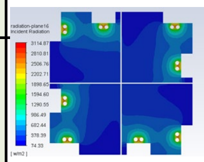
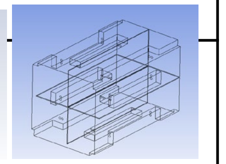
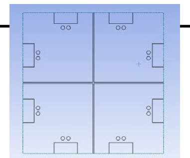
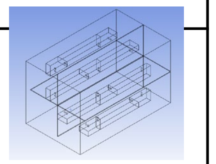
	K [m2/J]	D [J/m2]		%
MS2 RH 74-85 %	0.043	74.1	0.958676	95.85
MS2 RH 32-50 %	0.038	74.1	0.940143	94.02



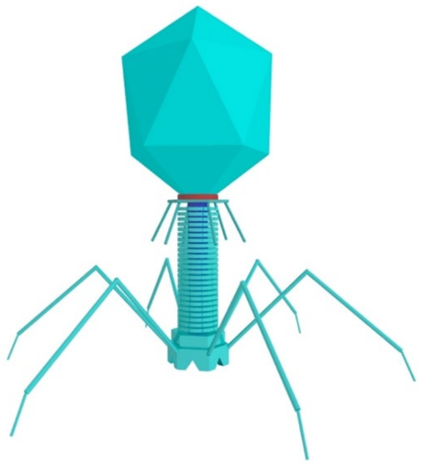
From ref. | CFD Results | Below the required 99%

10 lamps

	K	D [J/m2]		%
MS2 RH 74-85 %	0.043	75.4	0.960922	96.09222
MS2 RH 32-50 %	0.038	75.4	0.943028	94.30283

CFD runs	D_{CFD}	Survival - $s = e^{-k*D_{CFD}}$		$Dose\left[\frac{mJ}{cm^2}\right] = A\cdot(loginactivation) + B\cdot(loginactivation)^2$		Illustration
	$UV\ Dose\left[\frac{J}{m^2}\right]$	$k = 0.043\left[\frac{m^2}{J}\right]$ MS2 RH 74-85 %	$k = 0.038\left[\frac{m^2}{J}\right]$ MS2 RH 32-50 %	Max. log inactivation	$Simulated\ RED\left[\frac{mJ}{cm^2}\right]$ Constant A=4.12 Constant B=0.573	
Case#1 – **MID 8 Lamps** Sym. Arrangement Wall reflection **77%**	$74.1\left[\frac{J}{m^2}\right]$	95.85%	94.02%	1.38log	$RED = 6.79\left[\frac{mJ}{cm^2}\right]$	
Case#2 - **MID 8 Lamps** Sym. Arrangement Wall reflection **20%**	$59.4\left[\frac{J}{m^2}\right]$	92.3%	89.5%	1.13log	$RED = 5.39\left[\frac{mJ}{cm^2}\right]$	
Case#3 - **Close to inlet 8 Lamps** Non Sym. Arrangement	$67.8\left[\frac{J}{m^2}\right]$	94.6%	92.4%	1.26log	$RED = 6.084\left[\frac{mJ}{cm^2}\right]$	 
Case#4 - **Close to inlet 10 Lamps** Non Sym. Arrangement	$75.4\left[\frac{J}{m^2}\right]$	96.1%	94.3%	1.43log	$RED = 7.041\left[\frac{mJ}{cm^2}\right]$	
Case#5 - **MID 8 Lamps** Non Sym. Arrangement + middle reflectors	$67.8\left[\frac{J}{m^2}\right]$	94.6%	92.4%	1.2log	$RED = 5.786\left[\frac{mJ}{cm^2}\right]$	 
Case#6 - **MID 8 Lamps** Non Sym. Arrangement + middle reflectors	$74.1\left[\frac{J}{m^2}\right]$	95.85%	94.02%	1.33log	$RED = 6.516\left[\frac{mJ}{cm^2}\right]$	 

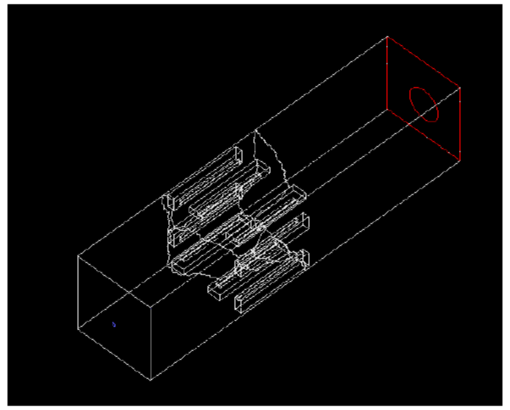
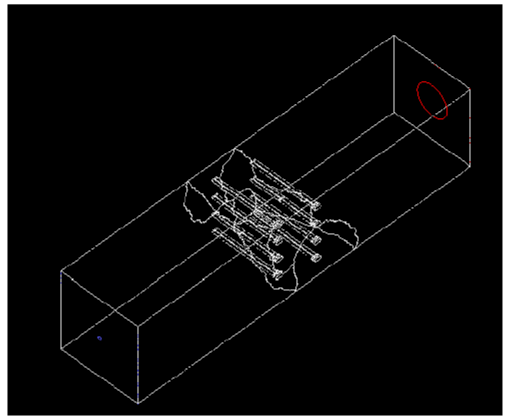
MS2 virus at different flow rates



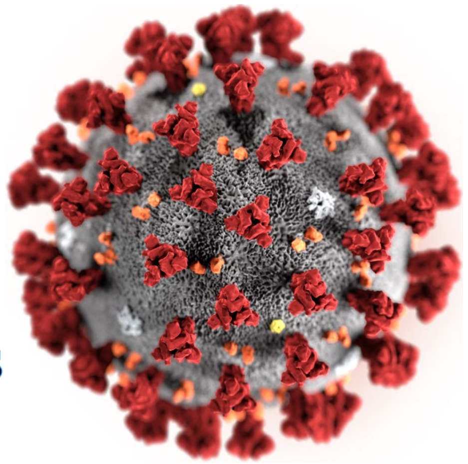
It was found that the CFD results are in a good agreement with the findings obtained from the empirical tests.

CFD runs	D_{CFD}	Survival - $s = e^{-k*D_{CFD}}$		$Dose\left[\frac{mJ}{cm^2}\right] = A \cdot (loginactivation) + B \cdot (loginactivation)^2$		Lab Tests
	$UV\ Dose\left[\frac{J}{m^2}\right]$	$k = 0.043\left[\frac{m^2}{J}\right]$ MS2 RH 74-85 %	$k = 0.038\left[\frac{m^2}{J}\right]$ MS2 RH 32-50 %	Max. log inactivation	$Simulated\ RED\left[\frac{mJ}{cm^2}\right]$ Constant A=4.12 Constant B=0.573	
6000 [m3/h]	$29.4\left[\frac{J}{m^2}\right]$	71.5%	67.1%	0.65 log	$RED = 2.918\left[\frac{mJ}{cm^2}\right]$	0.64 log (77.2%)– 14/9/22 0.78 log (83.3%)– 10/10/22 0.65 log (77.5%)– 28/11/22
4000 [m3/h]	$44.1\left[\frac{J}{m^2}\right]$	85.0%	81.3%	0.94 log	$RED = 4.405\left[\frac{mJ}{cm^2}\right]$	1.3 log (95.3%)– 24/10/22 1.3 log (95.2%)– 28/11/22 0.9 log (87%)– 6/12/22 0.69 log (79%)– 20/12/22 1.0 log (90%)– 27/12/22
2000 [m3/h]	$87.2\left[\frac{J}{m^2}\right]$	97.6%	96.3%	1.71 log	$RED = 8.695\left[\frac{mJ}{cm^2}\right]$	1.0 log (90%)– 11/10/22 0.79 log (84%)– 6/12/22 0.59 log (74%)– 20/12/22 0.79 log (84%)– 27/12/22

Perpendicular vs Parallel

CFD runs	D_{CFD} $UV\ Dose \left[\frac{J}{m^2}\right]$	Survival - $s = e^{-k*D_{CFD}}$		$Dose \left[\frac{mJ}{cm^2}\right] = A \cdot (loginactivation) + B \cdot (loginactivation)^2$		Lab Tests
		$k = 0.043 \left[\frac{m^2}{J}\right]$ MS2 RH 74-85 %	$k = 0.038 \left[\frac{m^2}{J}\right]$ MS2 RH 32-50 %	Max. log inactivation	$Simulated\ RED \left[\frac{mJ}{cm^2}\right]$ Constant A=4.12 Constant B=0.573	
	$44.1 \left[\frac{J}{m^2}\right]$	85.0%	81.3%	0.94 log	$RED = 4.405 \left[\frac{mJ}{cm^2}\right]$	1.3 log (95.3%)– 24/10/22 1.3 log (95.2%)– 28/11/22 0.9 log (87%)– 6/12/22 0.69 log (79%)– 20/12/22 1.0 log (90%)– 27/12/22
	$98.5 \left[\frac{J}{m^2}\right]$	98.55%	97.6%	1.87 log	$RED = 9.708 \left[\frac{mJ}{cm^2}\right]$ **Improves Log-inactivation Of The System By 45%.**	N/A

Comparison to SARS-COV2 virus



It was found that the CFD results are in a good agreement with the findings obtained from the empirical tests

CFD runs	D_{CFD} $UV\ Dose \left[\frac{J}{m^2}\right]$	Survival - $s = e^{-k*D_{CFD}}$	$Dose \left[\frac{mJ}{cm^2}\right] = A \cdot (loginactivation) + B \cdot (loginactivation)^2$		Lab Tests
		$k = 0.4 \left[\frac{m^2}{J}\right]$	Max. log inactivation	$Simulated\ RED \left[\frac{mJ}{cm^2}\right]$ Constant A=0.4 Constant B=0.0325	
6000 [m3/h]	$29.4 \left[\frac{J}{m^2}\right]$	99.9992%	5.11 log	$RED = 2.893 \left[\frac{mJ}{cm^2}\right]$	N/A
4000 [m3/h]	$44.1 \left[\frac{J}{m^2}\right]$	100%	7.0 log	$RED = 4.382 \left[\frac{mJ}{cm^2}\right]$	N/A
2000 [m3/h]	$87.2 \left[\frac{J}{m^2}\right]$	100%	11.25 log	$RED = 8.614 \left[\frac{mJ}{cm^2}\right]$	N/A

SARS-CoV-2	MS2	T4	phi6
ssRNA	ssRNA	DNA	dsRNA
29,900 b	3,569 b	169,000 bp	13,500 bp
Membrane coated	No membrane	No membrane	Membrane coated

Conclusions

- A flow rate of 4000 m^3/hr is optimal for UV inactivation of MS2 in air ducts.
- Perpendicular UV lamps improve efficiency by 45% over parallel orientation.
- MS2 is about ten times more resistant than SARS-CoV-2.
- Nebulizer UVT with MS2 in 1:40 nutrient broth is needed to replicate organic surroundings.

Thanks