Coil Cleaning: UV Fundamental Sizing and Energy Savings

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ABSTRACT

Nearly every HVAC engineer has had the experience of opening a unit to find the drain pan and coil covered with a slimy residue of mold biofilm. Not only these conditions can be unhealthy and occasionally deliver unpleasant smell for building occupants, but it also ruins the heat transfer capacity of the system and consequently increases the energy operating cost.

Various coil-cleaning methods have been used to try to control this problem. Many of those techniques involve the use of detergents or even solvents, which can pose safety issues - health and flammability, for example – and high pressure washing that diminishes the life of the coil, because sometimes acids are involved. Often coil cleaning isn't done with regularity and even when it is done on schedule, the mold growth can return in a very short time, usually less than a month.

The use of germicidal ultraviolet light (UV-C) technology in air-handling systems now allows for a proactive method of keeping the coil clean and operating in "as new" performance all the time. UV-C lights can be added to air handlers and other pieces of equipment through a relatively simple and low cost retrofit kit. Energy based payback ranges from 2 years to as low as 6 month depending upon the cost of electricity and the operating conditions.

Interestingly, while UV-C light has been promoted for its positive impact on indoor air quality (IAQ), the "bottom line" impact - its contribution to system energy efficiency and lower maintenance costs - might ultimately be considered to be its greatest asset.

What Causes the Mold Biofilm Build-Up?

Five conditions will result in mold and fungus growth causing a biofilm that inhibits fin heat transfer:

1. A source of mold spores. Sufficient mold spores are found in nearly every environment and brought into the building through door openings and outdoor air supplies.

2. Even when HEPA filtration is used, the filter replacement causes a momentary breach of the sterility barrier that allows airborne mold spores to contaminate and colonize the coils.

3. Organic material on which the mold can grow. Dust and particles of organic material are also readily available in every system, even with the best filtration systems.

4. The right temperature range. Temperatures from 50° F to more than 100° F provide the right incubation range.

5. Moisture, which is in more than adequate supply on cooling coils and drain pans of all air conditioning units.

Even when filtration is provided, a large part of the build-up on the cooling coil is the result of biological growth.

Effects of Biofilm Growth on a Cooling Coil

The presence of a biofilm on the fins of a coil has two direct effect:

1) **Major Heat transfer loss** to the fins due to the much lower thermal conductivity of the organic biofilm covering the aluminum fins.
2) **Slight Pressure drop increase** due to the restriction of the flow area and consequently a reduction of the air flow delivery capacity.

As we will see in the following example, a biofilm growth can have significant impact on coil performance, putting it considerably off design specification.

If we consider the case of a cooling coil of 8 ft high by 9 ft wide that has consequently 72 sq ft. of face area and 29,150 cfm our gross face velocity is about 400 ft per minute. But this is not the actual velocity inside the coil between the fins. The fin and tube material do block a significant portion of the face coil area.

Let's consider a typical coil of 12 fins per inch of 0.0055 inch thickness with copper tubes of 1/2" on a vertical Row Tube Spacing of 1.5 inch and horizontal Face Tube Spacing of 1.3 inch. As the air flowing at 400 ft/min enters the fins, it has to accelerate up to 428 ft/min to maintain the rate due the blockage of the free cross section area. If we also consider that there are 72 face rows of tubes, the available free area is further squeezed down and the resultant inner coil velocity goes up to 740 ft/min.

How does a bio-film build-up affect the performance? If the bio-film thickness is 1.5 thousandth of an inch (i.e. half the thickness of a common paper sheet) on the fin and tube surfaces, this will reduce the free area down some more and increase the velocity up to 793 ft/min. What will an increase of 53 ft/min (793-740) mean to pressure drop? Well, surprisingly, not much. Calculation shows that the pressure drop of his fouled coil will increase by only 0.09” of water column which is hardly noticeable and quite difficult to measure. This means that when a high pressure drop due to fouling is observed, that coil is then extremely fouled.

If we now consider the effects of biofilm fouling on the heat transfer coefficient, we will see that this is where the performance loss is severe.

A cooling coil is a liquid to air heat exchanger and as such its heat duty **Q** is the product of a heat transfer coefficient **U**, a heat transfer surface **A**, and the temperature difference between the hot air and the cooling fluid often called “delta T”and written **ΔT**. Hence the well-known basic heat transfer formula:

$$\mathbf{Q = U\ A\ \Delta T}$$

When a tiny biofilm builds up on a coil, it adds an insulating layer on the heat transfer surfaces. This additional layer reduces the heat transfer coefficient **U**. Because the physical heat transfer surface cannot be changed, in order to maintain the heat exchange duty **Q**, only the temperature differential **ΔT** can be increased to compensate. The only way to do this consists in decreasing the cooling fluid temperature and consequently make the whole HVAC system (compressors, chillers, auxiliary equipment, etc.) work harder to produce a cooler fluid. Otherwise, the cooling heat duty of the coil is lost in the same proportion as the heat transfer coefficient reduction.

Now let’s look at how much drop in heat duty a 0.0015 inch biofilm can cause. Such as biofilm is hardly visible as it is about half of a paper sheet.

The flow in the small gap between fins has a low enough Reynolds number to be laminar and as such a constant Nusselt number can be used to calculate the convective heat transfer coefficient. The overall heat transfer coefficient **U** is calculated by adding the thermal resistance of the biofilm to the air boundary layer convective resistance.

$$\mathbf{U} = \frac{1}{\frac{1}{h} + \frac{t}{k}}$$

Where ***h*** = convective heat transfer coefficient of the air stream on the clean fins

k = thermal conductivity of the biofilm material

t = biofilm thickness

Using well-known heat transfer data from available literature, the clean **U** value of the coil described above is found to be 7.32 BTU/hr/ft^2/ºF. The presence of our 0.0015 inch biofilm that has a thermal conductivity of 0.003 BTU/hr/ft/ ºF brings this number down to 5.78 BTU/hr/ft^2/ºF, hence a huge loss of 21% of the heat transfer coefficient **U** !

To maintain the heat duty performance of the coil, the temperature differential must be increased by the same ratio. This will be done by lowering the cooling fluid temperature which will negatively impact the coefficient of performance (COP) of the chiller. In order to be conservative in estimating the consequential reduction of the COP value, we will consider that the system trend is proportional to the best possible case i.e. the ideal Carnot cycle, which can be written as follows:

$$COP \backsim \frac{Th}{Th-Tc}$$

Where: ***Th = Temperature of the Hot environment where heat is rejected***

Tc = Temperature of the chiller Cooling fluid

Hence the new COP will be calculated according to the following relation:

$$COP_{new} = \frac{Th-Tc}{Th-Tc\_new} COP$$

Based on the above, the COP will decrease from 3.0 down to 2.75. This drop in COP will cause the energy consumption of the cooling system to increase by 8.9 % to compensate for the fouling of the coil.

Based on the above described fundamental physical principles of heat transfer and fluid flow applied to HVAC coils, Sanuvox Technologies has programmed an engineering calculation methodology to estimate the energy savings by keeping coils free of biofilms and the consequential return on investment.

INPUT PARAMETERS OF THE CALCULATION PROGRAM

Here is an overview of all the parameters involved in the calculation and a brief description of their importance and impact on the final result.

PLEASE, FILL IN THE BASICS INFORMATIONS

WHAT IS THE:

		UNITS
Cooling Coil Height ?	**99**	inches
Cooling Coil Width?	**106**	inches
Cooling Coil Thickness?	**12**	inches
Air temperature entering the coil?	**80**	deg. F
Relative Humidity of air entering the coil	**75**	%
Air temperature leaving the coil?	**50**	deg. F
Chilled water inlet temperature?	**40**	deg. F
Cost of electricity?	**0,100 $**	/kWh
% operating time?	**25**	%
% operating load?	**80**	%
Length of lamps required?	**40**	inches
Number of lamps required?	**4**	
Cost of replacement per lamp?	**100**	$
Estimated UV system cost with install?	**2500**	$
Actual annual coil cleaning cost?	**500**	$

OPTIONAL: OTHER INFORMATIONS if needed

WHAT IS THE:

	Default value		
Number of fins per inch?	12		
Fin thickness?	0,006		inch
Cooling tube outside diameter?	0,500		inch
Row Tube Spacing (Horizontal pitch)	1,500		inch
Face Tube Spacing (Vertical Pitch)	1,299		inch
Chiller COP?	3,0		
Coil face air inlet velocity?	400		ft/min
Biofilm thickness?	0,0015		in
Biofilm thermal resistance?	0,003		BTU/hr.ft.R
Interfin Moody friction factor?	0,18		
Air thermal conductivity?	0,0211		BTU/hr.ft.R

OUTPUT OF THE CALCULATION PROGRAM

CALCULATED VALUES

	Value	/units		Value	/units
Average air density	0,076	lb/ft3	Pressure drop accross clean coil	0,595	in.wc
Coil face area	73	ft2	Pressure drop accross fouled coil	0,685	in.wc
Number of Tube Face Rows	76		Pressure drop increase to biofilm fouling	0,090	in.wc
Number of Tube Rows	8		Increase fan power due to coil fouling	0,526	kW
Coil effective area	21 454	ft2	Clean coil heat transfer coefficient	7,32	BTU/hr.ft2.R
Air flow	29 150	ACFM	Fouled coil heat transfer coefficient	5,78	BTU/hr.ft2.R
Air velocity between fins	428	ft/min	Heat tranfer reduction due/biofilm fouling	21,0%	
Air velocity between fins /tube crossing	740	ft/min			
Spacing between fins	0,078	in	Sensible heat absorbed by the coil	955 287	BTU/hr
Spacing between fins with biofilm	0,0748	in	Latent heat absorbed by the coil	1 141 984	BTU/hr
Air velocity between fins with biofilm	445	ft/min	**Total heat duty of the coil**	**2 097 271**	**BTU/hr**
Air velocity between fins with biofilm	793	ft/min			
Entering Air Humidity saturation pressure	0,513	psia	Normal operating LMTD of clean coil	13,4	deg.F
Entering Air dew point temperature	71,4	deg.F	**Operating LMTD of dirty coil**	**16,9**	**deg.F**
Exiting air saturation pressure	0,178	psia	Decrease cold water temp/maintain capacity	3,6	deg.F
Total air mass flow rate	132 691	lb/hr	Chiller normal COP	3,00	
Water content in air entering the coil	2 187	lb/hr	**Chiller operating COP at fouled LMTD**	**2,75**	
Water content of the air exiting the coil	1 010	lb/hr	Energy loss due to the reduced COP	8,9%	
Total water condensed	1 177	lb/hr	Clean Cooling coil operating cost	22 429 $	per year
Annual coil cleaning cost	500	$	Extra cooling cost due to bio-fouling	24 424 $	per year
UV system installed cost	2 500	$			
UV system electrical operating cost	350,40	$ year	Difference	1 995 $	per year
UV system lamp maintenance cost	200,00	$ year	Fan operating cost due to fouling	461 $	per year
Return on investment	**12,5**	**months**	**TOTAL extra operating cost due to bio-fouling**	**2 457 $**	**per year**

PAYBACK

Applying the heat duty based calculation program on the cooling coil described above provides a payback of a year. The payback will be faster for systems with:

- **larger heat transfer surface (width, height, thickness, # fins per inch)**
- **higher electricity cost**
- **higher % operating load**
- **higher % operating time**
- **higher relative humidity / dehumidifying process**
- **lower cooling system COP value**

COMMENTS ABOUT THE INPUT PARAMETERS :

1) Coil height, width and thickness are essential values along with the number of fins per inch to calculate the heat transfer surface **A** of the coil. An error on any of these 3 parameters will significantly and proportionally affect the final operating cost. Great care must be taken for these values.

2) Air temperatures in and out as well as cooling fluid temperatures in and out are used in the calculation of the temperature differential **ΔT** and since they are the second multiplier in the heat duty equation, they will affect directly the final operating cost. Also very important to have reasonably accurate values.

3) Cost of electricity is very important, needless to say. The higher it is the better the return on investment by keeping the coil performance to its optimum.

4) **% Operating Time:** the real cooling requirements (not free cooling) typically occurs during the hottest season. A season theoretically lasts 25% of the year, but the real cooling season can be as small as 15% of the year (i.e. about 50 days) in northern climates such as Canada and be as high as 80% of the year as we get near the equator. We suggest to pick 25% as a default guess value. Here again, it will directly affect the final operating cost and should be revised accordingly if the cost seems too high or too low.

   Here's a suggested list of values based on reported monthly Cooling Degree-Days[1] (CCD) from the literature:

Canada and North USA:	**15%**
Mid USA:	**25%**
Southern USA:	**50%**
Australia:	**50%**
Middle-East	**65%**

5) **%Operating Load**: given that HVAC engineers design the systems based on average local climate conditions, there is a significant safety margin taken in the design. Therefore, in extremely rare hot conditions, the operating load can occasionally reach 90% of installed capacity, but in general, the average operating load throughout the cooling season is expected to be somewhere around 60% + or – 10%. Here again, it will directly affect the final operating cost and should be revised accordingly if the cost seems too high or too low.

[1] Definition of 'Cooling Degree Day - CDD'
The number of degrees that a day's average temperature is above 65° Fahrenheit and people start to use air conditioning to cool their buildings. To calculate the CDD, take the average temperature of a day and subtract 65. For example, if the day's average temperature is 80°F, its CDD is 15. If every day in a 30 day month had an average temperature of 80°F, the month's CDD value would be 450 (15 x 30).

6) COP : Coefficient of Performance of the chiller unit that supplies the cold fluid for the coil. This value is the ratio of the amount of free energy that a heat pump can grab in the ambient outside air to the energy consumption required to drive the cycle. It varies considerably from as low as 2 for single stage heat pumps used in light commercial/residential units up to 5 for large industrial ultra-efficient cooling cycles. A conservative default value of 3 is used in the calculation. Its value will significantly affect the final operating cost.

7) Biofilm thickness is a default value that should not be played with too much. It has been set conservatively at a default value of 0.0015 inch which is less than half a standard paper sheet. Its value can have evidently a huge effect on performance and final results.

8) All the other parameters do not have as much impact on the final results and unless there are very clear and specific information provided by the clients, they shall remain untouched.

HOW MUCH UV IS REQUIRED TO ELIMINATE BIOFILM AND RESTORE COIL EFFICIENCY ?

UV coil cleaning can bring performance back to the original operating conditions.

Typical coil cleaning methods include chemical treatments and/or steam cleaning. However, recent evidence suggests that both methods can be ineffective. Chemical cleaning may only remove surface growth while leaving material still embedded in the center of the fin pack. Some reports indicate that high pressure steam cleaning can actually force the surface growth deeper in the fin pack compressing the growth material so tightly that the only solution may be a new coil. Both methods can also be detrimental to most of today's heat transfer enhanced fins surfaces.

Coil cleaning is certainly necessary, but cannot be done economically with the frequency and level that will keep the coil operating at design conditions on a daily basis. In essence, with UV-C lights, coil cleaning becomes a continuous, automatic and labor-free alternative. The UV-C light works by attacking the DNA of the mold and rendering it sterile so that it cannot reproduce.

Comparing physical cleaning methods to the use UV-C light is analogous to the difference between treating the symptoms rather than curing the disease.

UV-C technology is not new, as it has proven itself for years as a way to provide sterilization in medical and food processing applications. Given a properly engineered sizing methodology, UV-

C lights can clean up a coil already contaminated by mold growth and keep the coil cleaner far better than any other methods.

The effectiveness of the UV-C light is a function of the light intensity and exposure time. Aluminum coil fins are a good reflective surface and, as a result, the UV-C energy is capable of penetrating several row coils with excellent results.

FUNDAMENTALS OF UV SIZING FOR HVAC COILS

In order to make sense of the sizing rules applicable to UV coil cleaning, it is essential to have a good understanding of 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 $\mathbf{E}_\lambda$, of a value connected to the light wavelength according to the Planck-Einstein relation:

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

Where

$\boldsymbol{h}$ = Planck's constant, 6.626×10^{-34} Joule.sec

$\boldsymbol{c}$ = Speed of light in vacuum, 2.998×10^{8} m/sec

$\boldsymbol{\lambda}$ = wavelength in m (usually expressed in nanometers)

Using the above Planck-Einstein relation, the energy conveyed by each UV-C photon at a wavelength of 253.7 nm is equal to 7.83×10^{-19} Joule. Therefore the number of photons per Joule is the inverse i.e. 1.28×10^{18} photons per Joule.

Keeping in mind that one watt of power is defined as one joule of energy per second, then a UV intensity of 100 Watt/m^2 provides a flow of 1.28×10^{20} photons per second per square meter. Considering that a virus of 0.2 micron diameter has a cross-sectional area of $3.14 \times 10^{-14} m^2$, despite its tiny size, this virus will be bombarded by 4 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. In reality, 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 particular distribution of its DNA sequence.

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:

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

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 $\boldsymbol{S}$ and can be expressed as:

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

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

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

As explained above, 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:

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

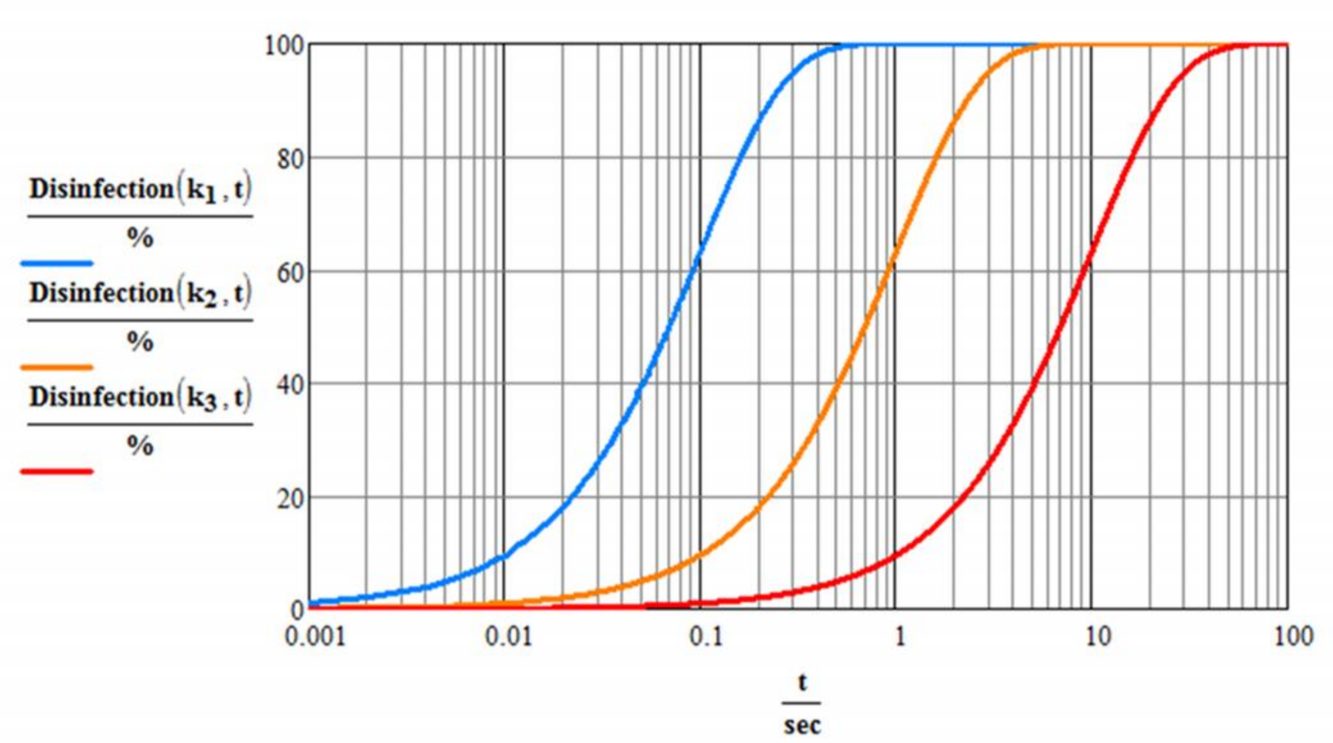
By substituting equation (6) in equation (5), we finally get the well verified germicidal UV Dose-Response relation:

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

Equation 7 illustrates that a given dose results in a given 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. The residence time for any in-duct disinfection will be of the order of a few seconds or a fractions of a second depending on airflow velocities. Therefore, the UV intensities for neutralization of an airborne microorganism are required 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 1 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 example being a chemical concentration multiplied by the contact time.

Fig.1 Disinfection rate –vs- UV exposure time for various UV susceptibility



Susceptibility of microorganisms to UV energy

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.

Based upon equation 5, it is clear that 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 in 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 90% disinfection of a population of influenza-A virus using the following formula:

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

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 published literature. The following table shows the organisms are universally found in the biofilm of HVAC coils and their UV susceptibility constant k. The organisms are ranked by their UV susceptibility, the toughest organism at the top of this list is **Aspergillus Niger**. It is a common contaminant of food called black mold. It is ubiquitous in soil and is commonly reported from indoor environments. Because Aspergillus Niger has the highest D90 value, it makes good engineering sense to use it as a reference criteria for UV coil disinfection system sizing.

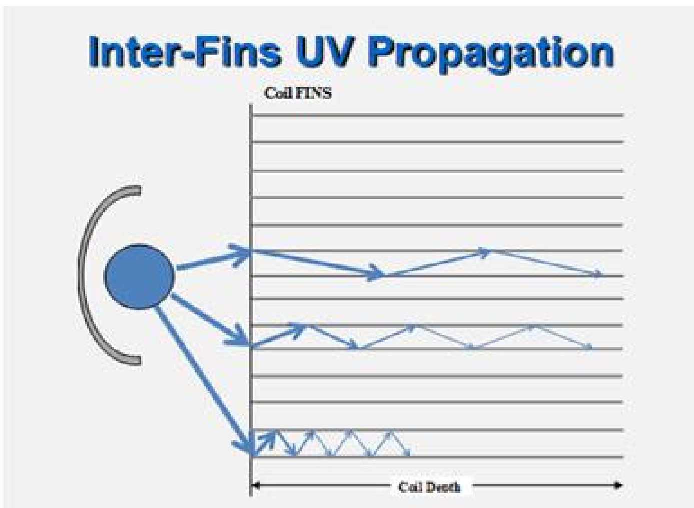
Bio-contaminant	k in AIR or Surf		D 90%	microJ/cm2	microJ/cm2
	Custom unit		mJ/cm2	900 000	1 800 000
---	---	---	---	UV Dose	UV Dose
				3600 sec @	3600 sec @
				250 microW/cm2	500 microW/cm2
Aspergillus niger spores	0,00058	m2/J	397,07	99,4593%	99,9971%
Aspergillus fumigatus spores	0,00103	m2/J	223,59	99,9906%	100,0000%
Cladosporium herbarum	0,0037	m2/J	62,24	100,0000%	100,0000%
Mucor mucedo	0,00399	m2/J	57,72	100,0000%	100,0000%
Candida albicans	0,00407	m2/J	56,58	100,0000%	100,0000%
Trichophyton rubrum	0,00411	m2/J	56,03	100,0000%	100,0000%
Penicillium chrysogenum	0,00434	m2/J	53,06	100,0000%	100,0000%
Algae blue-green	0,00512	m2/J	44,98	100,0000%	100,0000%
Bacillus Cereus spores	0,00564	m2/J	40,83	100,0000%	100,0000%
Penicillium digitatum	0,00718	m2/J	32,08	100,0000%	100,0000%
Botrytis cinerea	0,0092	m2/J	25,03	100,0000%	100,0000%
Fusarium oxysporum	0,0142	m2/J	16,22	100,0000%	100,0000%
Bacillus subtilis spores	0,0155	m2/J	14,86	100,0000%	100,0000%
Mucor spores	0,01645	m2/J	14,00	100,0000%	100,0000%
Clostridium tetani	0,04699	m2/J	4,90	100,0000%	100,0000%
Yeast	0,05756	m2/J	4,00	100,0000%	100,0000%
Serratia marcescens	0,095	m2/J	2,42	100,0000%	100,0000%
Pseudomonas aeruginosa	0,1047	m2/J	2,20	100,0000%	100,0000%
E. Coli	0,15611	m2/J	1,48	100,0000%	100,0000%
Aeromonas	0,2031	m2/J	1,13	100,0000%	100,0000%
Salmonella	0,221	m2/J	1,04	100,0000%	100,0000%
Listeria monocytogenes	0,2303	m2/J	1,00	100,0000%	100,0000%
Legionella pneumophila	0,44613	m2/J	0,52	100,0000%	100,0000%
Mycobacterium tuberculosis	0,4721	m2/J	0,49	100,0000%	100,0000%

Table 1. UV susceptibility of bio-contaminants commonly found on HVAC coils

As it can be seen from table 1, an exposure of 1 hour at a UV intensity of 250 microwatt/cm2 delivers a UV dose of 900,000 microJoule/cm2 which is sufficient to disinfect over 99% of Aspergillus Niger at the surface of the coil. Not surprisingly, when the UV intensity is doubled, the disinfection rate increases accordingly and reaches 99.99%.

Given that the reproduction doubling rate of a mold colony can be of the order of magnitude of a one or two day given the sufficient availability of heat, food and water to sustain their metabolism, it is tempting to conclude that the above dosage is more than sufficient to maintain a coil free from mold growth. Mathematically expressed, the tipping point for UV to win the battle against the multiplying molds is when the kill rate due to UV is equal to the birth rate of the molds. One can easily deduce that the UV must at least kill the whole new mold generation within 24 hours.

However, because the coil is not a unidimensional flat surface but rather a three dimensional assembly of parallel fins with a depth of several inches, sometimes even up to 16" thick, the initial UV intensity on the fin edge surface has to propagate by multiple reflections to reach all the inter-fin surfaces. The following illustration shows geometrically the UV light intensity decay as it propagates by multiple reflection between coil fins.



Inter-Fins UV Propagation

1 reflection : UV = **80%**

2 reflection : UV = 80% x 80%= **64%**

3 reflection : UV = 80%x80%x80%= **51%**

4 reflection : UV = 80%x80%x80%x80%= **41%**

5 reflection : UV = 80%x80%x80%x80%x80%= **33%**

6 reflection : UV = 80%x80%x80%x80%x80%x80%= **26%**

7 reflection : UV = 80%x80%x80%x80%x80%x80%x80%= **21%**

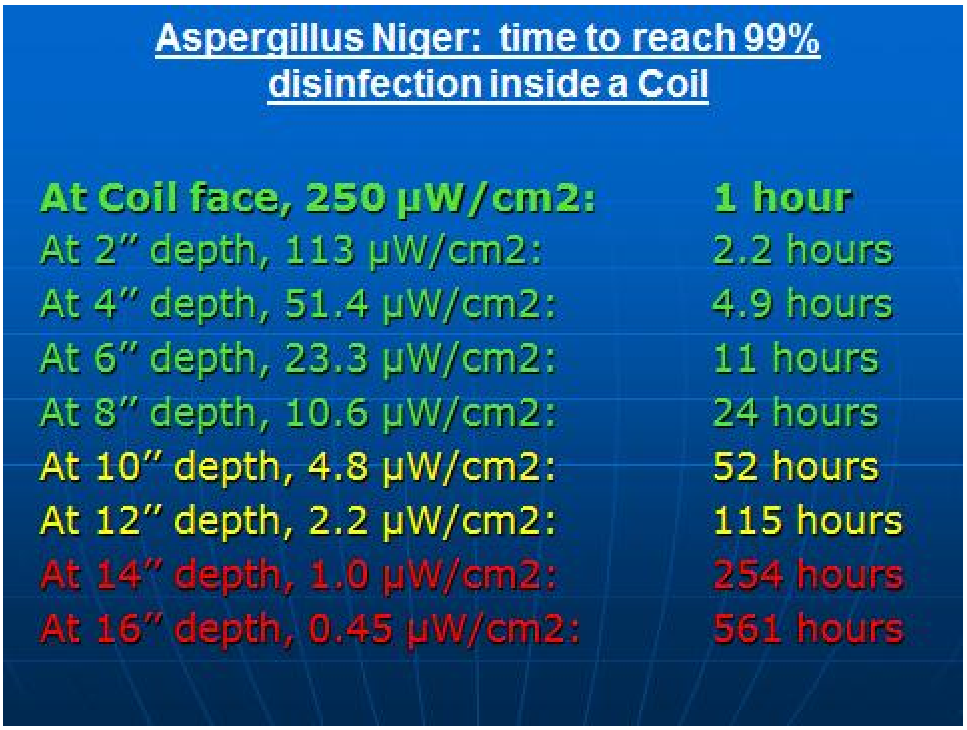
8 reflection : UV = 80%x80%x80%x80% x80% x80% x80% x80%= **17%**

9 reflection : UV = 80%x80%x80%x80%x80%x80%x80%x80%x80%=**13%**

10 reflection : UV = 80%x80%x80%x80%x80%x80%x80%x80%x80%x80%=**11%**

Aluminum is an excellent UV reflector that reflects 80% of the incident UV intensity. Consequently after each reflection, 20% of the UV energy is lost. After the second reflection the intensity drops to 64% (80% x 80%), after 3 reflections it is down to 51%, and so on. After 10 reflections, the intensity is down to 11%.

Let’s have a closer look at the final effect this UV intensity decay has on the effective disinfection time as we go deeper and deeper inside the coil.



Aspergillus Niger: time to reach 99% disinfection inside a Coil

At Coil face, 250 µW/cm2:	1 hour
At 2” depth, 113 µW/cm2:	2.2 hours
At 4” depth, 51.4 µW/cm2:	4.9 hours
At 6” depth, 23.3 µW/cm2:	11 hours
At 8” depth, 10.6 µW/cm2:	24 hours
At 10” depth, 4.8 µW/cm2:	52 hours
At 12” depth, 2.2 µW/cm2:	115 hours
At 14” depth, 1.0 µW/cm2:	254 hours
At 16” depth, 0.45 µW/cm2:	561 hours

What the above table tells us is that a surface intensity of 250 microwatt/cm2 can provide a suitable disinfection of coil fins to overcome the mold growth rate up to a coil depth up to 8 or 10 inches. For thicker coils, it is recommended to do the sizing based on doubling the initial surface intensity to 500 microwatt/cm2, thus getting less than 30 minutes survival time for Aspergillus Niger on the immediate coil surface. For very thick coils above 14 inches it is preferable to install UV lamps on both sides of the coil. The above discussion clearly demonstrates that the adequate power sizing and design layout of the UV lamps in front of a coil is of critical importance to the successful application of this technology.

UV Intensity Design Level for Coil Cleaning

As we all know, light intensity varies significantly with the distance from the lamps. In addition, the physical geometry, number of lamps, and UV lamps positions all have the potential to affect the overall distribution of the UV intensity on a given coil. Only a computerized program using an integration method and summation of the contribution of all the UV lamps allows to precisely calculate the UV irradiation field on a coil face.

Many manufacturers size systems by rules of thumb, such as filling the available cross-section with an almost continuous array of lamps at a constant spacing, or base their designs on limited proprietary testing. Unfortunately, these rudimentary rule of thumbs often end up using too much or too little UV intensity, which either makes the UV coil cleaning technology too expensive or deceptively inefficient at keeping the coil free from biofilm nuisance.

The following image illustrates the typical output provided by a proper UV sizing software.

Installation

Coil Width 120 in
Coil Height 120 in
Distance between lamp and coil 18 in

Lamp Length 40 in
Number of Rows 2
Number of Lamps per Row 2

Lamp Position on Coil* UPSTREAM
*Lamp Cooling Effects will occur on a Downstream Installation

Lamp Fouling* NO FOULING
*Lamp Fouling will occur on a Downstream Installation

Total number of lamps and fixtures required 4
Total Input Power Required 413 W

Coil surface UV Irradiation Intensity

Minimum UV Irradiation Intensity 545 $\mu W/cm^2$
Average UV Irradiation Intensity 1102 $\mu W/cm^2$
Maximum UV Irradiation Intensity 1705 $\mu W/cm^2$

Survival time of ASPERGILLUS NIGER
with disinfection rate of 99 %

Maximum survival Time 28 min
Average Survival Time 14 min
Minimum Survival Time 9 min