

# ESTIMATING THE EFFECTS OF AMBIENT CONDITIONS AND AGING ON THE PERFORMANCE OF UVGI AIR CLEANERS

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## ABSTRACT

Ultraviolet germicidal irradiation (UVGI) uses UVC radiation produced by low pressure Hg vapor lamps to control biological air contaminants. Lamp UV output depends on multiple factors, including accumulated operating time (age) and the thermal effects of ambient air temperature and velocity. Additionally, the life of some lamp types depends on the frequency of on-off cycles. Models of lamp life as a function of cycling rate and lamp output as a function of age and ambient conditions are developed for three common standard output lamp types based on heat transfer theory and manufacturer's lamp performance data. Example results are presented and a parametric study in the form of a 3<sup>k</sup> factorial experiment is used to identify significant factors affecting output and their interactions. A typical range of ambient conditions reduces lamp output by more than 30% of rated capacity and the inclusion of aging effects reduces capacity by as much as 70%. For given ambient conditions, performance varies substantially across lamp types due to their differing heat transfer characteristics. It is concluded that short term and long term variation of lamp output is highly significant and that modeling of such effects is necessary for accurate system design and analysis.

## KEYWORDS

Ultraviolet Germicidal Irradiation, Indoor Air Quality

## INTRODUCTION

Ultraviolet radiation is a portion of the electromagnetic spectrum with wavelengths from 100 - 400 nm. The International Commission on Illumination (CIE 1987) divides the UV spectrum into three bands; UVA (315-400 nm), UVB (280-315 nm) and UVC (100-280 nm). Ultraviolet germicidal irradiation (UVGI) is the use of radiation mainly from the UVC band, to control microorganisms such as viruses and bacteria, by damaging their genetic material, thus rendering them incapable of reproducing. For a given level of control, UVGI can significantly reduce ventilation rate and filtration efficiency requirements, which may make it an attractive alternative or complement to these established methods (First, et al. 1999).

The two main types of UV generators are low and medium pressure mercury lamps (Philips 2005). The spectra of radiation emitted by the two types are different, as shown in Figure 1, which also shows relative germicidal effectiveness as a function of wavelength. For germicidal applications, low pressure lamps are most effective, because they emit most (~90%) of their radiant energy in the germicidal wavelength band around 253.7nm in the UVC part of the spectrum. Medium-pressure mercury lamps produce a different spectrum with more energy in the UVB range and are sometimes applied in water disinfection and for treatment of certain skin diseases. Since this study is concerned with UVGI air disinfection, only the characteristics of standard output low pressure lamps are considered.

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Lamps are further distinguished by the starting method, which may be hot cathode or cold cathode. The cathodes of hot cathode lamps must operate above ambient temperature while those of cold cathode lamps do not. Hot cathode lamps are identical in electrical characteristics to the standard preheat design fluorescent lamp which operates on a typical preheat circuit with a starter. Their electrodes are tungsten filaments coated with an alkaline earth oxide that emits electrons when heated. Each start causes wear on the filament, which eventually fails. Cold cathode lamps have sturdy cylindrical electrodes instead of filaments, and the lamp is started instantly by means of a high voltage rather than by a starter. This type of electrode seldom wears out.

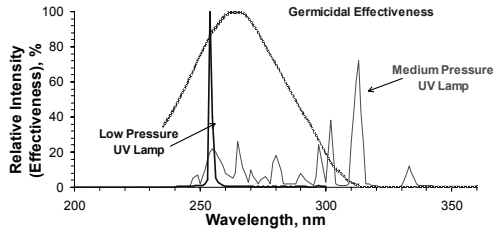


Figure 1. Comparison of typical low and medium pressure mercury vapor lamp spectra with relative germicidal effectiveness (figure courtesy of W.J. Kowalski)

Literature review indicates that the following parameters may affect the life and output of UV lamps:

- *On/off cycling rate* (Philips 2005). The higher the cycling rate (frequency of starts) the shorter the life for hot cathode lamps because the tungsten filaments deteriorates with each cycle.
- *Age*, i.e., total burning time (Philips 2005). The output of germicidal lamps slowly decreases with accumulated operating hours as the tube gradually loses its ability to transmit the short wavelengths of ultraviolet light.
- *Cold spot temperature* (CIE 2003). Ambient air flow and temperature affect the lamp surface temperature which controls UV output by changing the vapor pressure of the mercury in the lamp. Lamp power, shape, and orientation to the flow also affect the cold spot temperature.
- *Humidity* (ARTI 2002). Water molecules in the air stream will absorb a portion of UV radiation emitted by a lamp in proportion to absolute humidity. Published measurements (ARTI 2002) indicate that this is a minor effect for typical conditions and optical path lengths. It is, therefore, neglected in this analysis.

Cycling rate and burning time are cumulative in their effects, while cold spot temperature and humidity have immediate and short term effects. Together, cycling, aging, and ambient conditions can reduce the UV output relative to the rated output of a new lamp by more than 50%. Consequently, accurate models of lamp behavior are important for sizing and evaluation of UVGI systems. However, this issue has received little attention in published investigations of UVGI or in design guidance. The objective of this investigation was to develop models of lamp output and life based on published performance characteristics and to explore the impacts of cycling rate, age, air velocity and temperature via a parametric study.

## METHODOLOGY

### Lamp type and configurations

Three common standard output UVGI lamp types were studied: 1) cylindrical hot cathode, 2) twin tube hot cathode, and 3) cylindrical cold cathode. Lamp characteristics are summarized in Table 1.

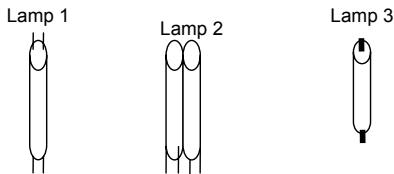


Figure 2. Lamp shapes

Table 1. Lamp Characteristics

Lamp	1	2	3
Length (mm)	437	385	357
Diameter (mm)	28	18*	15
Rated Life (hr)	8000	9000	17500
Power (W)	25	60	10

Note: \* One tube. Overall width is 38mm

The impact of air flow and temperature on lamp surface temperature was estimated for a cross flow arrangement, which is the most common orientation used in ducted systems. The twin tube lamp is essentially two cylindrical tubes side by side (Figure 2). Because of this asymmetry, the rotation of the lamp about its axis affects its performance. Two positions were considered: (a) bluff body flow, in which the plane through the centerlines of the tubes is perpendicular to the direction of air flow, and (b) streamline flow, in which this plane is parallel to the direction of flow.

### Cold spot temperature

The effect of cold spot temperature on lamp output is shown in Figure 3.

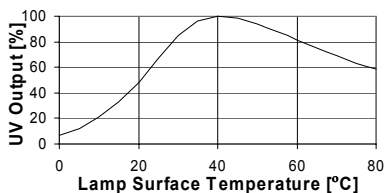


Figure 3. UV lamp output as a function of lamp surface (cold spot) temperature (Philips 2005)

Cold spot temperature was approximated by the lamp surface temperature, calculated by a heat balance (Eq. 1) that included the fraction of lamp input power dissipated as heat ( $Q_{total}$ ), convective losses ( $Q_{conv}$ ), and radiative losses ( $Q_{rad}$ ). A manufacturer of UV lamps advised that approximately 75% of the input power of a typical lamp is dissipated as thermal energy (Philips 2007). This factor was used to calculate  $Q_{total}$  from catalog data. It was assumed that input power was not affected by ambient conditions.

$$Q_{total} = Q_{conv} + Q_{rad} \quad (\text{Eq. 1})$$

In terms of the Nusselt number, the convective heat loss from a lamp is

$$Q_{conv} = \frac{Nu \cdot k \cdot A \cdot (T_s - T_{amb})}{D} \quad (\text{Eq. 2})$$

The Nusselt number for free, mixed and forced convection regimes was determined by three different sets of equations which were valid in different ranges of Reynolds number (varying mainly as a function of ambient velocity). The correlations for heat transfer from an isothermal horizontal cylinder in cross flow were used for lamps 1 and 3; while the models for isothermal ellipse were used for lamp2.

Equations 3 and 4 give the Nusselt numbers for natural (Morgan 1975) and forced (Churchill and Bernstein 1977) convection on a cylinder (Lamps 1 and 3), respectively.

$$\overline{Nu}_N = 0.47 \cdot (\text{Pr} \cdot Gr)^{1/4} \quad (\text{Eq. 3})$$

$$\overline{Nu}_F = 0.3 + \frac{0.62 \cdot Re_d^{1/2} \cdot Pr^{1/3}}{\left[1 + \left(\frac{0.4}{Pr}\right)^{2/3}\right]^{1/4}} \cdot \left[1 + \left(\frac{Re_d}{282,000}\right)^{5/8}\right]^{4/5} \quad (\text{Eq. 4})$$

The Nusselt number for Lamp 2, which has twin tubes, was approximated by correlations for an ellipse (Zhukauskas and Ziugzda 1985) as shown in Eq. 5.

$$\overline{Nu}_{d1} = 0.27 \cdot Pr^{0.37} \cdot Re_{d1}^{-.6} \quad (\text{Eq. 5})$$

Where  $d_1$  denotes the axial length that is parallel to the flow.

The Nusselt number for mixed convection on a ellipse was assumed to be the similar to that for a cylinder (Morgan 1975).

$$Re_i = \left[\frac{\overline{Nu}_N}{0.583}\right]^{1/0.471} \quad (\text{Eq. 6})$$

$$Re_{eff} = \sqrt{Re_i^2 + Re_d^2} \quad (\text{Eq. 7})$$

$$\overline{Nu}_M = 0.583 Re_{eff}^{0.471} \quad (\text{Eq. 8})$$

Radiation was modeled using standard methods for gray enclosures (Eq 9). The emissivity of the quartz lamp surface was assumed to be 0.93 (WWW 2007).

$$Q_{conv} = \varepsilon \cdot A \cdot \sigma \cdot \left[(T_s + 273)^4 + (T_{amb} + 273)^4\right] \quad (\text{Eq. 9})$$

### Aging and cycling

Figure 4 shows a typical plot of lamp output vs. time. Output at the end of the rated lamp life is roughly 80-82% of the initial output. At any given point in lamp life, the change in output due to ambient effects was assumed to be scaled independently according to this function. Consultation with a lamp manufacturer also indicated that the shape of the depreciation curve shown in Figure. 4 is not affected by the cycling rate of hot cathode lamps. If lamp life is extended or shortened, the curve simply terminates at a different time (Philips 2007). The typical effect of cycling rate on life is shown in Figure 5 (Philips 2005), which was used to predict hot cathode lamp life. Note that the effect of switching rate is non-linear.

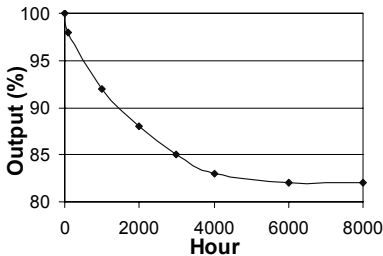


Figure 4. Relative output change as a function of burning time (for lamp life of 8000 hour)

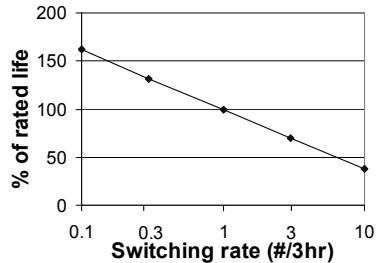


Figure 5. Predicted effect of switching rate on life of hot cathode lamp

### Parametric study

As described above, temperature, velocity, and age may affect the output of a UV lamp. In order to

study the combined effects of these factors, 27 cases comprising a 3<sup>3</sup> factorial design were analyzed (Table 2). Three levels of each factor were selected to represent a typical range of operating conditions: 15.6, 26.7, and 35°C for air temperature; 0, 2.03, and 5.08 m/s for air velocity; and new, 50 % of rated life, and end of life for age. The fourth key factor in lamp performance, cycling rate, only affects lamp life (time to failure), therefore, it was not included in the factorial design. However, it is easily determined that as cycling rate varies from a low value, say once per day to once per hour, life will decrease from 156% to 70% of the rated (once per 3 hr) value.

Table 2. Factorial design

Case	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Temperature	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
Velocity	1	1	1	0	0	0	-1	-1	-1	1	1	1	0	0	0	-1
Age	1	0	-1	1	0	-1	1	0	-1	1	0	-1	1	0	-1	1

Case	17	18	19	20	21	22	23	24	25	26	27
Temperature	0	0	-1	-1	-1	-1	-1	-1	-1	-1	-1
Velocity	-1	-1	1	1	1	0	0	0	-1	-1	-1
Age	0	-1	1	0	-1	1	0	-1	1	0	-1

Note: -1, 0, and +1 represent low, intermediate, and high levels of factors, respectively

## RESULTS AND DISCUSSION

### Ambient condition effects on new lamps

Since the total heat released from the lamp is assumed constant constant, the surface temperature decreases with either decreased air temperature or increased air velocity (Figure 6). The result of this variation in surface temperature is a variation in output of 20 – 30% of maximum (Figure 7). Low ambient temperature combined with high velocity has a particularly adverse effect on UV output, while output is fairly high and stable for temperature at or above typical room temperature.

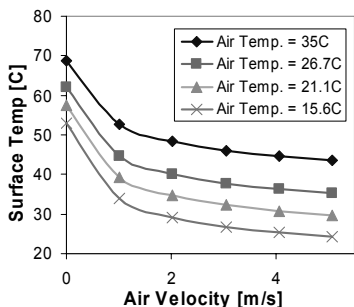


Figure 6. Variation of lamp 1 surface temperature with air temperature and velocity.

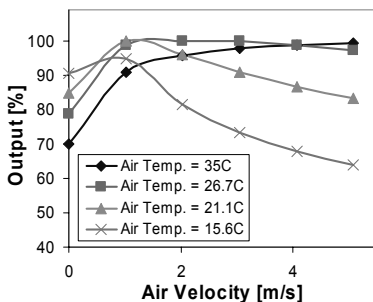


Figure 7. UV output variation of new lamp 1 with air temperature and velocity

Figure 8 shows the output variation with ambient conditions of lamp 2 in the bluff body and streamline configurations. As shown in Figure 8a, results are qualitatively similar to results for lamp 1 shown in Figure 7. However, the lower heat transfer coefficient in the bluff-body arrangement reduces cooling at lower air temperatures and results in generally higher output than the streamline flow configuration.

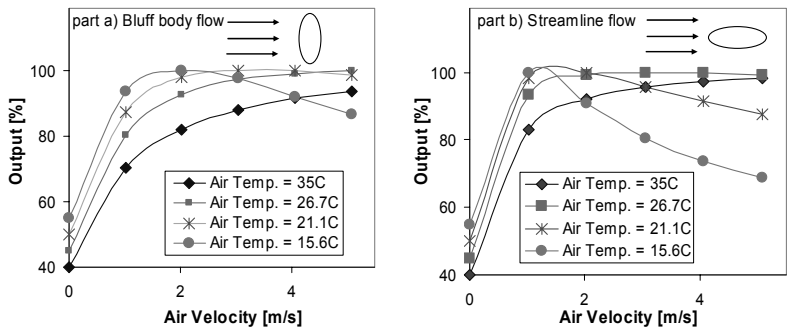


Figure 8. Output of lamp 2 for new lamps under different flow conditions (a) bluff body flow and (b) streamline flow

Figure 9 shows lamp output profiles of lamp 3 under varying ambient conditions. These are also qualitatively similar to lamp 1. The main difference is generally higher output, which is due to the relationship between lamp size and required steady state heat dissipation, which resulted in higher surface temperatures. Figure 10 presents the same data as Figure 9 in the form of a contour plot. It is apparent that there is a zone within which output is high, as well as ranges of conditions under which performance could be expected to deteriorate significantly.

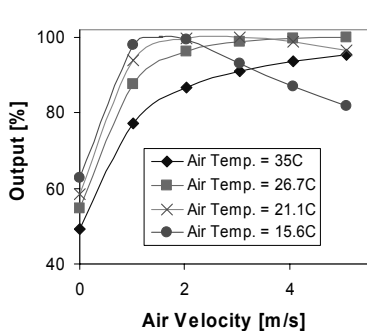


Figure 9. UV output variation of new lamp 3 with air temperature and velocity

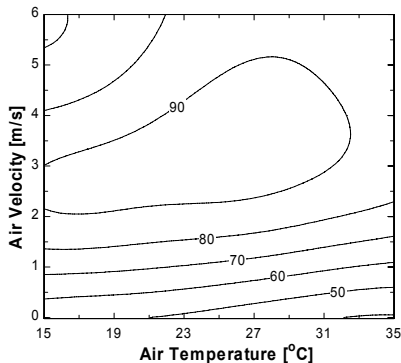


Figure 10. Contour plot of new lamp 3 output variation with air temperature and velocity

### Parametric study results

Table 3 summarizes the results of the 27 parametric analyses for various combinations of air velocity and temperature, and, and lamp type. The range of UV output variation is huge, from 32.8 to 100% of rated value, which strongly suggest that these parameters cannot be neglected during system design.

A general linear model was used to determine significant factors and interaction terms for lamp 1 as an illustration. The full model included all main factors and all 2<sup>nd</sup> order interaction terms but the 3<sup>rd</sup> order interaction was omitted. Two interaction terms were excluded from the full model in the final regression because of a high P-value. Only one interaction term, temperature\*velocity, is statistically significant

(P-value close to zero). The regression results are shown in Table 4 for both the full model and the final model for lamp 1. Temperature\*age and age\*velocity interactions were dropped from the final model because of their high P values.

Table 3. Predicted lamp output of for 3<sup>k</sup> factorial experiment

Case	% of Initial Rated Output				Range of output variation (Min– Max)
	Lamp 1	Lamp 2 (a)	Lamp 2 (b)	Lamp 3	
1	81.3	76.9	80.7	78.2	76.9 - 81.3
2	83.3	78.8	82.7	80.1	78.8 - 83.3
3	99.2	93.8	98.4	95.4	93.8 - 99.2
4	78.5	67.4	75.6	71.1	67.4 - 78.5
5	80.4	69.0	77.4	72.8	69.0 - 80.4
6	95.7	82.2	92.2	86.7	82.2 - 95.7
7	81.3	32.8	32.8	40.3	32.8 - 81.3
8	83.3	33.6	33.6	41.3	33.6 - 83.3
9	70.1	40.0	40.0	49.2	40.0 - 70.1
10	79.8	81.8	81.3	82.0	79.8 - 82.0
11	81.7	83.8	83.3	84.0	81.7 - 84.0
12	97.3	99.8	99.2	100.0	97.3 - 100.0
13	82.0	75.9	81.4	78.8	75.9 - 82.0
14	84.0	77.8	83.4	80.7	77.8 - 84.0
15	100.0	92.6	99.3	96.1	92.6 - 100.0
16	64.6	36.9	36.9	44.9	36.9 - 64.6
17	66.2	37.8	37.8	46.0	37.8 - 66.2
18	78.8	45.0	45.0	54.8	45.0 - 78.8
19	52.5	70.9	56.5	67.0	52.5 - 70.9
20	53.8	72.7	57.9	68.6	53.8 - 72.7
21	64.0	86.5	68.9	81.7	64.0 - 86.5
22	66.7	82.0	74.4	81.6	66.7 - 82.0
23	68.3	84.0	76.2	83.6	68.3 - 84.0
24	81.3	100.0	90.7	99.5	81.3 - 100.0
25	74.4	45.1	45.1	51.4	45.1 - 74.4
26	76.2	46.2	46.2	52.7	46.2 - 76.2
27	90.7	55.0	55.0	62.7	55.0 - 90.7
Min	52.5	32.8	32.8	40.3	
Max	100.0	100.0	99.3	100.0	

## CONCLUSIONS

Results of this modeling exercise indicate that variations in UV lamp output due to lamp type and ambient conditions can be of equal or greater magnitude than depreciation due to aging. These changes are cumulative and can reduce lamp output by nearly 70% over a range of typical conditions found in ducted UVGI systems installed in heating, ventilation, and air-conditioning systems. Consequently, design procedures should take these sources of output variation into consideration.

Table 4. Regression analysis of factors influencing output for lamp 1– temperature, velocity and age

Predictor	Full Model			Final Model		
	Adjusted Mean Square	F-Statistic	P-Value	Adjusted Mean Square	F-Statistic	P-Value
Temp	506.8	15.94	0.002	506.8	17.58	0
Velocity	85.57	2.69	0.128	85.57	2.97	0.08
Age	438.8	13.8	0.003	438.8	15.22	0
Temp*Velocity	367.29	11.55	0.002	367.29	12.74	0
Temp*Age	20.19	0.63	0.652			
Age*Velocity	31.52	0.99	0.465			
Error	31.80			28.83		
R <sup>2</sup>	93.63%			88.45%		

## NOMENCLATURE

D = Diameter of the lamp (m)

Gr = Grashof number (-)

Nu = Nusselt number (-)

Pr = Prandtl number (-)

Q<sub>total</sub> = Total heat released from the lamp (W)

Q<sub>conv</sub> = heat released from the lamp by convection (W)

Q<sub>rad</sub> = heat released from the lamp by radiation (W)

Re = Reynold number (-)

T<sub>s</sub> = Surface temperature of the lamp(°C)

T<sub>amb</sub> = ambient temperature around the lamp(°C)

## Subscript

d = with respect to diameter of the lamp (for Re)

d1 = with respect to axial length that is parallel to the flow (for Re)

eff = effective (for Re)

F = force convection flow (for Nu)

i = imaginary (for Re)

M = mixed convection flow (for Nu)

N = natural convection flow (for Nu)

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