Method for the Measurement of the Output of Monochromatic (254 nm) Low-Pressure UV Lamps#

Contributing authors on the IUVA Manufacturers' Council
Oliver Lawal (Aquisense), **Bertrand Dussert** (Xylem), **Craig Howarth** (Hanovia), **Karl Platzer** (Light Sources), **Mike Sasges** (Trojan), **Jennifer Muller** (Trojan), **Elliott Whitby** (Calgon Carbon), **Richard Stowe** (Fusion UV), **Volker Adam** (Heraeus), **Dave Witham** (UVDI), **Stuart Engel** (Sanuvox), **Phyllis Posy** (Atlantium) and **Arjan van der Pol** (Phillips)
Revised by
James Bolton (Bolton Photosciences) and **Michael Santelli** (Light Sources)
Send comments to Volker Adam (volker.adam@heraeus.com), Jennifer Muller (jmuller@trojanuv.com) or James Bolton (jbolton@boltonuv.com)

Context

This protocol has been developed to present a consistent methodology for the determination and benchmarking of UV lamp output from monochromatic (254 nm) lamps operated by a corresponding power supply (ballast). The protocol can be used for testing and comparing different lamp and ballast combinations, to compare test results from different laboratories and to compare operation under different ambient conditions. The protocol is not intended for general manufacturing quality control or quality assurance testing, or as a replacement for biodosimetry for determining the dose in UV water treatment systems. The protocol should be conducted by someone who is a UV expert and preferably by a third-party independent contractor.

These tests only yield information on the UV efficiency of the lamp being tested in the orientation in which it is tested (often but not exclusively horizontally) under open-air conditions where the lamp is allowed to achieve a steady-state with the surrounding still air at room temperature. The results cannot be extrapolated to the UV efficiency of UV lamps under other conditions, such as inside a quartz sleeve in a UV reactor, unless thermal operating conditions of the lamp are taken into account under each circumstance.

Monochromatic lamps include tubular low pressure and low pressure high output (e.g., amalgam) lamps that are typically used in water and air treatment (e.g., disinfection, AOP etc.) applications. The protocol described herein is not recommended for medium pressure, pulsed, folded, non symmetrical or other special lamps (e.g., excilamps – also called excimer lamps).

Formula

Based on the work of Keitz (1971), the following formula is recommended for calculating the total UV output from a UV lamp with a monochromatic (e.g., 254 nm) output. The lamp output power P can be calculated from Equation 1 (the Keitz formula)*:

$$P = \frac{E 2 \pi^2 D L}{2\alpha + \sin 2\alpha} \qquad [1]$$

where (see Figure 1)
> E is measured irradiance (W m^{-2})
> D is distance (m) from lamp center to the UV sensor.
> L is the lamp arc length (m) from electrode tip to electrode tip.
> α is the half angle (radians) subtended by the lamp at the sensor position. That is, $\tan \alpha = L/(2D)$

This expression has been tested by comparing with goniometric measurements of lamp output, and by comparing results from laboratories in different countries (Sasges et al.
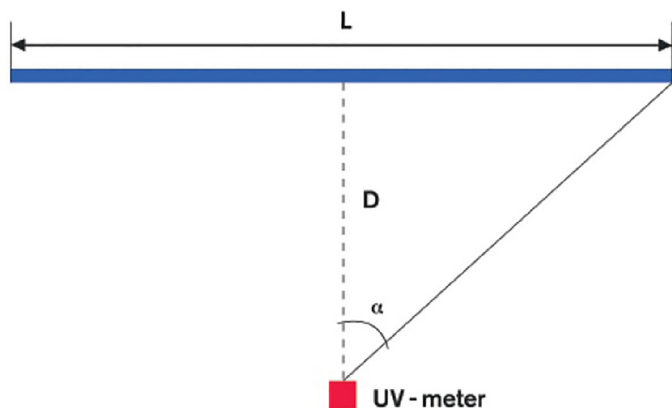

Figure 1. Geometry of the measurement system.

2007). The results are considered accurate within 5 percent and have shown good agreement between laboratories.

Necessary conditions

1. Measurements shall be conducted in still room air, not in a moving air stream.
2. The lamp orientation shall be horizontal.
3. Reflected light must be avoided (e.g. through use of baffles, differential measurement with beam stops). Appendix A examines two possible methods that can account for or minimize reflection.
4. The UV sensor must have an adequate cosine response for the lamp length and distance used. Cosine response means that the UV meter should have an output that is proportional to the cosine of the angle of the input beam to the normal to the UV meter surface.
5. In order to assure that the UV meter can "see" the entire arc length of the UV lamp, D should be at least twice L.[1]

Temperature conditions

Low-pressure and amalgam lamps are affected by their operating temperature, which is in turn affected by their surroundings, air temperature, etc. These lamps generally will exhibit increasing UV output with increasing temperature after ignition until an optimum temperature is reached, and then a decreasing output with further increases in lamp temperature. This behavior is shown in Figure 2, denoted as a "slightly overheated lamp." It is desirable to measure a lamp under these slightly overheated conditions, so that the maximum output can be measured. Lamps shall be measured at a stable and constant air temperature. The entire warm-up curve of irradiance vs. time shall be reported including the maximum peak. Room temperature shall be documented and included in the report.

Measurements

The lamp output reported shall be measured after a new-lamp 100 h burn-in period. The lamp output reported shall be based on lamps operating under air conditions, in which the lamp has reached a maximum output and then decreases to steady

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A draft of this protocol was originally published in 2008.

* A glossary of terms is provided in Appendix A.

[1] For the condition where $D = 2L$, the field of view is ±14° (28° full view). The recommended cosine response should be an $f2$ factor (according to CIE publication 69 or DIN 5032) of 1.5 percent or less for class A rating, within this field of view. The cosine response will be verified in the Validation of Cosine Response section of this protocol.

state, indicating that the lamp has passed through an optimum into an overheated condition. This will generate a UV irradiance curve as a function of time, which will illustrate the maximum and steady state output values.
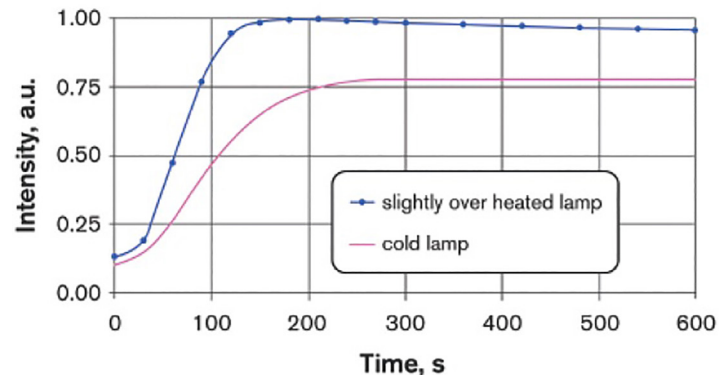

Figure 2. Lamp output vs. time after ignition for a slightly overheated lamp and for a lamp that does not reach its optimum temperature.

Lamp and ballast efficiency
Lamp output power is generally compared with the electrical (line) power consumed in order to calculate the efficiency of the lamp/ballast system, or compared to the electrical power delivered to the lamp to calculate the efficiency of the lamp. It is necessary that either electrical power be measured accurately, so the efficiency may be accurately determined. This electrical power measurement must be done using calibrated instruments for power measurement, using equipment such as power analyzers with adequate frequency response. In particular, it is not sufficient to measure the ballast voltage and current to obtain the lamp power by multiplication.

Calibrations
The following traceability of calibration, standard method must be confirmed, showing calibration within one year:

1. Radiometer with a detector traceable to a national laboratory (e.g. NIST, PTB, NPL, NRC etc.). The calibration for the UV radiometer used must be valid and traceable for calibration in the UVC range, and it must include a wavelength of 254 nm. If a spectroradiometer is used, then only the output between 250 and 260 nm shall be included in the calculated output.
2. The radiometer or spectroradiometer calibration to be validated by a qualified third party and/or accredited facility.
3. Confirmation for calibration of the power analyzer.

Detailed method
General remarks
1. Avoid reflected light during the measurement of the UV light.

a. Use non-reflecting materials, such as flat black paint, for walls, floor, baffles.

b. Be aware that the UV reflectance may be different from reflectance in the visible range.

c. Test: to check the amount of reflected light, compare the sensor signal to that measured when direct irradiation is blocked out, where a suggested procedure is described in Appendix B, part 1. Report the corrected result.

d. If reflection reduction is desired, a suggested method is described in Appendix B, part 2.

Safety

1. Do not expose uncovered skin or eyes to UV radiation.
2. Use adequate protective equipment, such as a UV safety shield, gloves and UV goggles. Not all plastic or glass safety glasses block UV below 300 nm. The transmission characteristics of safety glasses should be checked prior to use.

Equipment

1. Adjust the lamp and detector at a suitable height (e.g., 0.5 to 1.0 m) over the ground.
2. Check validity of calibration for all devices that influence results:
   a. radiometer
   b. spectroradiometer
   c. electrical equipment (power analyzer, multimeter)
   d. thermometer
   e. Make sure the electrical power measurement equipment is appropriate for the desired measurement.
3. Warm up all devices.

Validation of cosine response

1. The cosine correction for radiometers and spectroradiometers is critical to the proper measurement of the UV irradiance. The cosine correction must be confirmed by the following method for each lamp and detector combination, so that the lamp measurements are consistent within and between laboratories.
2. Validation of cosine response and the resulting minimum distance D_{min} where measurements for a given combination of lamp and detector can be performed as follows:
   a. Take readings of the UVC Detector for different distances (detector position perpendicular to lamp axis), recommended range from $D = L/2$ to $4L$.
   b. Take several readings of the UVC irradiance. For example, moving the detector from the closest point to the most remote point and then back again.

c. Average the irradiance readings for each distance.

d. Calculate the UVC power from the measured irradiances using Equation 1 (the Keitz formula) for each distance.

e. Plot calculated UVC power versus distance.

f. At a certain distance (D_{min}) the UV output should become independent of distance. Generally one finds that $D_{min} > 2L$.

g. Measure at least at one distance greater than D_{min}.

3. The distance derived by this method is valid for the combination of this lamp length and this individual detector.

Measurement procedure

(instructions to the person supervising the tests)

1. Record or monitor ambient temperature (±1 °C tolerance). The measurement thermometer should be near the test apparatus but not in a region where the temperature would be affected by heat from the lamp.
2. Determine that the distances for radiometer readings are valid.
3. Start recording the readings (UVC irradiance, electrical measurements, etc.) after the lamp is turned on.
4. Sampling rate: should be matched to the rate of changing of the UV intensity readings.
5. Rate of ~1 reading every 10 s is often sufficient to mark the maximum.
6. Record the ambient temperature again after the lamp has been turned off.
7. Calculate peak and steady state UV power using the Keitz formula. The peak UV power value is the value where the influence of temperature is reduced to a minimum and which can be compared to results of other laboratories.
8. Calculate the lamp efficiency either based on lamp power (Equation 2a; top) or power from the wall (Equation 2b; bottom) (optional) as:

$$\text{Efficiency (based on lamp power)}(\%) = 100 \times \frac{\text{Total UV Output (W)}}{\text{Total Power to the Lamp (W)}}$$

$$\text{Efficiency (based on wall power)}(\%) = 100 \times \frac{\text{Total UV Output (W)}}{\text{Total Power from the Wall (W)}}$$

Report content

Measurement report to include:

1. Description and certification of the organization and persons supervising the tests.
2. Full and detailed information about the lamp (e.g., manufacturer, identification etc.).

3. Full and detailed information about the ballast (e.g., manufacturer, identification etc.).

4. Lamp orientation during testing (horizontal required).

5. Active arc length L (between the ends of the filaments for "linear" lamps).

6. Measurement of the distance D from lamp center (with tolerance) to the "calibration plane" of the radiometer detector.

7. Room temperature (°C).

8. Sensor and radiometer brand, model number and serial numbers for the radiometer, detector and any filters or other optical elements (e.g., diffuser) on the detector.

9. Valid, traceable radiometer or spectroradiometer calibration documentation.

10. Plot of irradiance vs. time after ignition, with an indication of the peak irradiance values and the point on the curve where the efficiency calculations were made.

11. Calculated peak UV power with uncertainty, and fraction of reflected light subtracted to arrive at power reading. The uncertainty should include equipment uncertainty. The method to determine the reflected light should be stated.

12. Electrical power meter (e.g., brand, model number and serial numbers for the power meter). Confirmation of calibration or calibration certificate for the electrical power meter.

13. Measured voltage and current into the ballast.

14. Measured electrical power across the lamp and "from the wall" with uncertainty.

15. Calculated lamp efficiency (%) both with respect to the electrical power consumed by the lamp and the "from-the-wall" (optional) electrical power.

References

Keitz. H.A.E. 1971. Light Calculations and Measurements, Macmillan and Co. Ltd., London, UK.

Sasges, M.R., van der Pol, A., Voronov, A. and Robinson, J.A. 2007. Standard Method for Quantifying the Output of UV lamps, Proc. International Congress on Ozone and Ultraviolet Technologies, Los Angeles, CA, August, International Ultraviolet Association, PO Box 28154, Scottsdale, AZ, 85255. ■

Appendix A: Glossary of Terms

D – distance (m) from the center of the UV lamp to the calibration plane of the UV meter.

E – *irradiance* defined as the radiant power P of all wavelengths incident from all upward directions on a small element of surface containing the point under consideration divided by the area of the element. The units mW cm^{-2} are commonly used; 1 mW cm^{-2} = 10 W m^{-2}.

L – arc length (m) of the UV lamp

Appendix B: Two Suggested Methods to Minimize the Effects of Reflected UV

1. Detector mask method of reflection measurement

In this method, a black cardboard or wooden mask is placed at a distance about $D/2$ from the lamp, where the size and the positioning of the mask casts a complete shadow over the detector. The mask should be of a size that completely blocks the direct rays from the lamp, but not much larger (e.g., a width about 110 percent of the lamp length). See Figure 3 for a possible setup where the rectangular removable mask is used only when measuring the reflected UV. In this case the irradiance reading E_{refl} from the detector represents only UV reflected from the floor, ceiling and walls. E_{refl} should be subtracted from the overall irradiance reading and should represent less than 1-2 percent of the total irradiance at the detector.

Figure 3. Diagram of a possible setup for the mask method that allows measurement of reflected UV

2. Two-chamber method of reflection measurement

UV can reach the UV sensor by reflection from walls, the floor and the ceiling. This reflected UV must be avoided or subtracted from the detector signal in order to get proper irradiance values. A two-sector approach can be used for this purpose.

In this method, the test chamber is divided into two light-tight sectors, with the divider between the two sectors at least 35 cm from the center of the UV lamp. The lamp and detector should be mounted at least 25 cm (preferably about 1 m) from the floor and preferably about 1 m from the wall behind the lamp.

A rectangular hole 3 cm longer than the arc length and 2 cm wider than the width of the lamp should be cut in the divider, so that the UV sensor can "see" the entire arc length of the lamp through the hole. See Figure 4 for a possible setup.
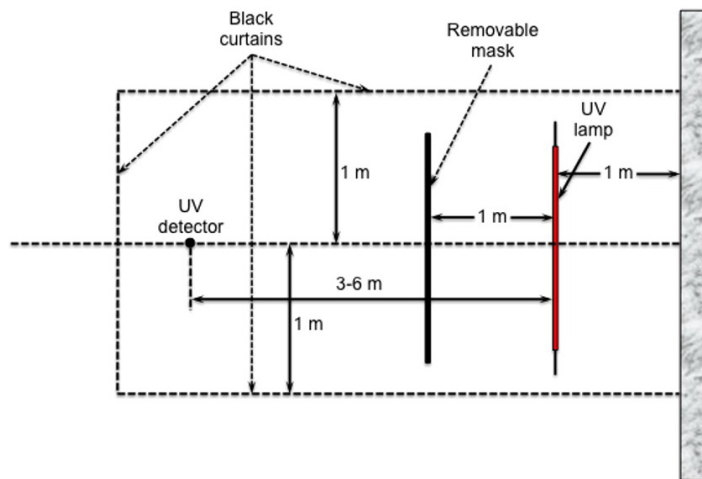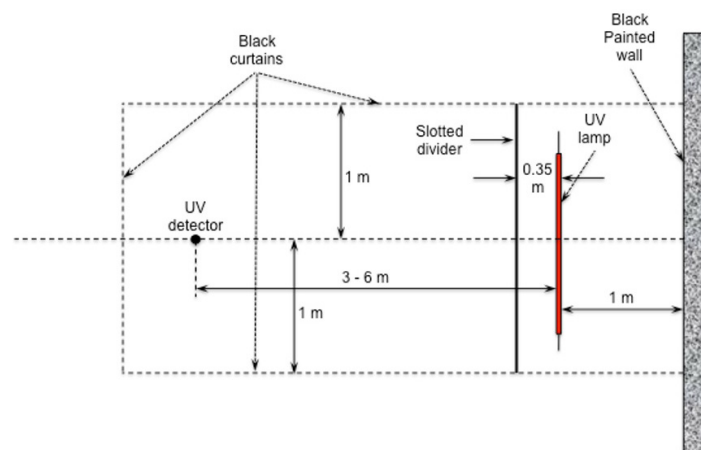

Figure 4. Diagram of a possible setup for the two-chamber method that minimizes reflected UV

Irradiance measurement procedure that minimizes the effect of reflection

When the two-chamber approach is used, the procedure is the same as that described in the main body of this protocol. In addition, a measurement should be made with the hole between the two chambers covered with black cardboard. The radiometer signal in that case should be virtually zero.

Appendix C: Example UV Lamp Testing Report

**Third-Party Report on UV Lamp Testing
of 250 W UV Lamps in Air**
by
Principal Tester
Consulting Company Name
Address
Telephone numbers
Email: _____
for
UV Lamp Company Name
Attention: Contact Person
Address
Telephone numbers
Email: _____

Date _____

Date of the tests: _____

Products tested: (description of UV lamps tested)

Objectives: To obtain performance data for the tested lamps, and specifically to determine:
- the UVC irradiance at 4.0 m
- the electrical operating parameters
- the UVC efficiency of the lamps using the IUVA Lamp Testing Protocol

Measurement equipment
Lamp ballast: manufacturer, model number and serial number
UVC radiometer: manufacturer, model number and serial number, date of calibration and attach a copy of the calibration certificate
Power analyzer: manufacturer, model number and serial number, date of calibration and attach a copy of the calibration certificate

Measurement protocols
- All UV lamps tested were "burned in" for a period of at least 100 h – see attached letter.
- The measurement protocols and calculations followed as far as possible the method proposed by the International Ultraviolet Association (IUVA).[3] The effi-

[3] Lawal, O., Dussert, B., Howarth, C, Platzer, K., Sasges, M., Muller, J., Whitby, E., Stowe, R., Adam, V., Witham, D., Engel, S., Posy, P., van de Pol, A., "Proposed Method for Measurement of the Output of Monochromatic (254 nm) Low Pressure UV Lamps," *IUVA News*, v.10, n.1, pp 14-16 (2008).

ciencies were measured as a function of the distance from the lamp, and a distance of 4.0 m was chosen, since efficiencies were found to be independent of this distance between 3 and 6 m from the center of the lamp. A two-chamber method was used to greatly reduce the reflected UV, which was measured and subtracted from the irradiance measurements.
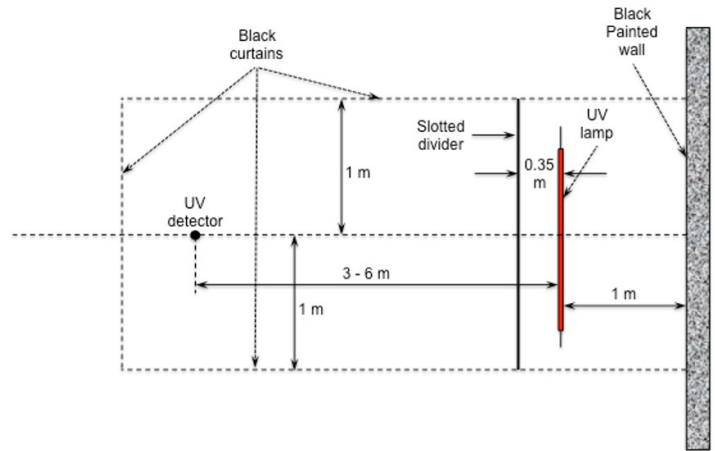- All lamps were mounted in air, horizontally, in a low-reflectance chamber (see Figures C1 and C2).

Figure C1. Diagram of the setup for lamp efficiency tests

Figure C2. Test chamber for the UV lamp efficiency tests

- The UVC detector was placed on a tripod mount at 4.0 m on a line out from the center of the lamp to the calibration plane of the detector and at the same height as that of the UV lamp (see Figure C3).
- A black-painted slotted divider was fabricated, which completely separated the lamp chamber from the detector chamber (see Figures C3 and C4). The divider had a rectangular hole 160 cm by 5.0 cm centered in the divider. This divider was mounted at a distance of 35 cm from the UV lamp and positioned so that the
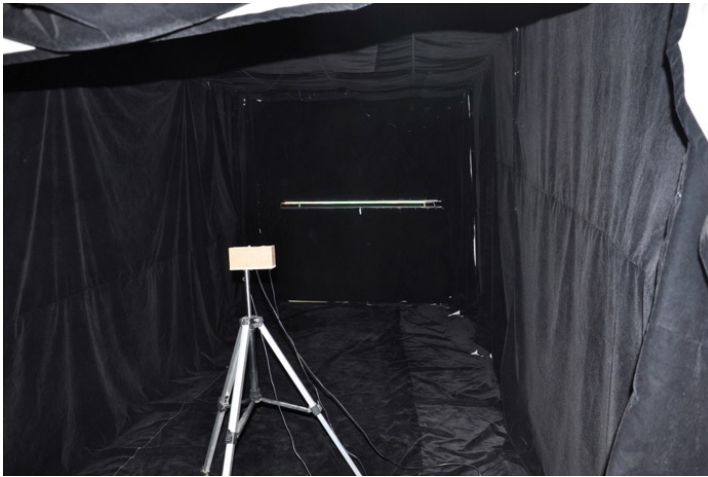
Figure C3. Detector chamber of the lamp testing setup

Figure C4. Lamp chamber of the lamp testing setup

entire UV lamp could be "seen" through the hole in the divider at the detector position.
- Periodically black-painted pieces were placed over the slot in the divider to block any direct rays from the lamp reaching the detector. The meter readings from this test (which indicated reflected UV from the walls that reached the detector) were subtracted from all meter readings. In fact, the reflected UV was undetectable when the slot was so covered.

The room temperature during the tests was 28°C.

Notes
- Measurement results are valid only for the individual setup and the tested lamps. Test results may vary based on different environmental conditions, such as in a water-filled reactor.
- All measurements were made at the time of the peak lamp output (peak irradiance). The reason is that UV lamps overheat in air, and consequently the efficiency can drop significantly. Since these UV lamps are designed to work inside a quartz sleeve with water flowing outside the sleeve, the lamp temperature would be controlled, so the peak efficiency is the appropriate calculation. In fact, for the lamps tested, the lamp efficiency was virtually independent of time after the time of peak irradiance.

Test results
Growth curve
Figure C5 shows the growth curve for one of the 250 W UV lamps. The lamp reached a "steady-state" at about 10 min and had a peak output at 92 s.
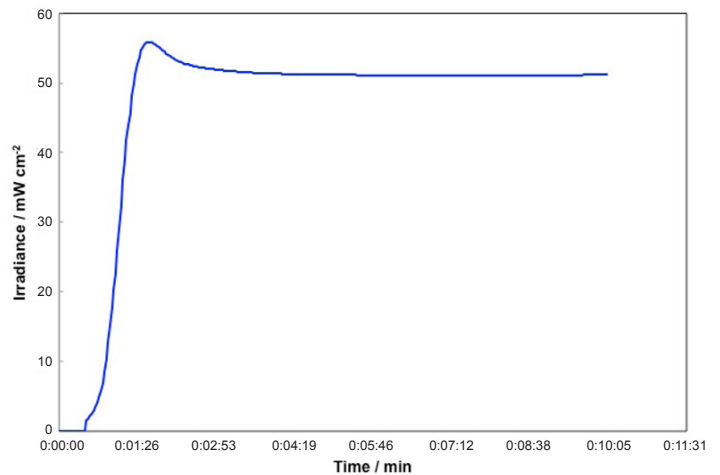

Figure C5. Growth curve for one of the tested 250 W UV lamps

Lamp efficiency vs. distance results

The radiometer detector was placed a various distance from the UV lamp. Table C1 shows the results.

Table C1. UV power calculated from the Keitz formula at various distances from the UV lamp

Distance from detector to lamp / m	Net irradiance / W m⁻²	Calculated UVC Power / W
2.00	2.280	97.7
3.00	1.190	109.8
4.00	0.690	111.3
5.00	0.442	111.3
6.00	0.307	111.2

It is clear that the calculated UVC power is independent of distance for distance greater than 4 m. Thus this distance was chosen as the distance for the testing.

Lamp efficiency results

Table C2 gives the test results for the 10 lamps tested.

Table C2. Raw data for the UV lamps tested in the air

Lamp No.	Time to Peak / s	Current / A	Voltage / V	True power[a] / W	Net irradiance[a,b] at 4.0 m / W m⁻²	Total UVC power[a,c] / W	UVC efficiency across lamp[e] / %
#23	98	1.752	173.0	302.7	0.690	111.3	**36.8**
#24	98	1.754	173.0	302.9	0.676	109.0	**36.0**
#13	100	1.753	177.0	301.0	0.694	112.0	**37.2**
#11	96	1.751	172.2	301.7	0.661	106.8	**35.4**
#14	98	1.748	175.0	306.9	0.695	112.2	**36.6**
#5	100	1.751	174.0	304.8	0.668	107.8	**35.4**
#10	110	1.747	174.0	304.1	0.678	109.4	**36.0**
#9	100	1.746	175.5	305.7	0.672	108.4	**35.5**
#6	98	1.754	172.4	301.9	0.661	106.8	**35.4**
#16	98	1.748	174.3	304.1	0.680	109.7	**36.1**
Averages		**1.750**	**174.0**	**303.6**	**0.677**	**109.3**	**36.0 ± 0.4** [d]

a. All measurements were made at the time of peak irradiance.

b. After subtracting the irradiance with a cardboard mask to block the direct UV light from the lamp, the radiometer readings were multiplied by the calibration factor 1.209.

c. Calculated using the Keitz formula: $P = \dfrac{E 2\pi^2 DL}{2\alpha + \sin 2\alpha}$,

where

E is the net measured irradiance (W m⁻²) at 254 nm

L is lamp length (1.465m) from electrode tip to electrode tip

D is distance (m) from lamp center to the sensor (here $D = 4.00$ m)

α is the half angle (radians) subtended by the lamp at the sensor position. That is, $\tan \alpha = L/(2D)$

d. The relative uncertainty is calculated as twice the standard deviation of the mean (95 percent confidence level).

e. The ratio of the power from the wall to the power across the lamp was found to be 0.927; hence, the average efficiency with respect to power from the wall is (33.4 ± 0.4) percent.

Note that the Keitz calculations were carried out for a distance 4.00 m from the lamp. Measurements were made at other distances (see Table C1), and it was established that when the radiometer detector is placed at 4.00 m from the UV lamp, it "sees" virtually the entire lamp with a cos θ response, and hence the lamp efficiencies, as calculated from the Keitz formula, are considered accurate at this distance.

Comments

1. Dr. _____ supervised and witnessed all lamp tests.
2. The efficiencies reported here are for lamps operated in open air. The efficiencies inside a quartz sleeve inside a UV reactor with water flowing outside the quartz sleeve will likely be different because of a different thermal environment around the lamp.
3. The lamps for testing were from among the stock of this lamp type and were selected at random by Dr. _____ from a set of 25 serial numbers. The selected lamps were then "burned-in" for 100 h.

Absolute uncertainty

The uncertainties given in Table C2 assess the relative uncertainty of the results. The principal source of the absolute uncertainty arises from the uncertainty of the radiometer calibration. The radiometer manufacturer states that this uncertainty is 5 percent. Thus, including the relative uncertainty, the absolute uncertainty is about 6 percent. Since the reflected light was undetectable when the port between the two chambers was blocked, reflected light does not contribute to the uncertainty.

Conclusions

The average lamp efficiency relative to power across the lamp was (36.0 ± 0.4) percent. The lamp efficiency with respect to power from the wall was (33.4 ± 0.4) percent.

The average peak UVC power emitted by the lamps was 109.3 W for an average electrical power input of 303.6 W (the electrical power at steady state was 276.7 W).

The average irradiance at 1.0 m from the lamps is estimated to be 8.27 W m⁻² or 0.827 mW cm⁻².