Method to determine the power efficiency of UV disinfection plants and its application to low pressure plants for drinking water

Alois W. Schmalwieser, Georg Hirschmann, Alexander Cabaj and Regina Sommer

ABSTRACT

In this paper we present a method to determine the power efficiency of ultraviolet (UV) disinfection plants and apply this to low pressure plants for drinking water. In UV disinfection plants the water flow is regulated to ensure that microorganisms receive the necessary fluence for inactivation while passing through. The flow depends on the UV transmission (UVT) of the water. The lower the UVT of the water is, the less water may flow through the plant. UV irradiance is produced by lamps that consume, together with other components, electrical power and entail running costs. The power efficiency – electrical power versus disinfected volume – of a plant has therefore an important impact. Applying this method to different UV plants that are on the market shows that electric power of at least 5.3 Wh is necessary to disinfect 1 m^3 of water possessing a UVT of 80% (100 mm), 8 Wh at 50% and 22 Wh at 10%. Further we found that ineffective design or a wrong selection of a plant may enhance these values by a factor of up to 7. This method enables not only the calculation of the power efficiency but also the decision for a certain plant type.

Key words | drinking water, low pressure lamps, power efficiency, UV disinfection

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INTRODUCTION

The first approach to disinfect drinking water by using ultraviolet (UV) radiation was undertaken in 1910 in Marseille, France (Henri *et al.* 1910). However, operational problems with the equipment led to a stop in the application. In the 1930s fluorescent lamps were developed and UV disinfection of air found broad acceptance (Council of Physical Therapy 1943), however, another two decades were needed until reliable applications in water became available. These first plants for UV disinfection of municipal drinking water were established in Austria and Switzerland in 1955 (Kruithof & van der Leer 1990). In the 1980s a few hundred UV disinfection plants were already installed. The growing amount of UV disinfection plants in Austria and mindful observations provoked the need for a national standard. In 1983 some of us participated in the preparation of the first national standard (ÖNROM M5873 1983) in the world. Experiences over the years led to an expanded version of the standard in 1996 (ÖNORM M5873 1996), and a biodosimetric test of plants (Cabaj *et al.* 1996) was required with a reduction equivalent fluence of at least 400 J/m^2. At the turn of the millennium more than 6,000 plants were already installed in Europe (Sommer *et al.* 2002). At this time the standard was divided into two parts separating low pressure (ÖNORM M5873-1 2001) and medium pressure application (ÖNORM M5873-2 2003). Nowadays this standard is accepted in several countries, such as the USA, France

doi: 10.2166/ws.2016.185

and others. The biodosimetric test procedure (Cabaj *et al.* 1996) does not only ensure proper disinfection but allows also a comparison of plants in respect of electric power efficiency, as we show here.

The biodosimetric test provides the maximal permissible water flow for each UV disinfection plant so that the necessary reduction equivalent fluence for disinfection (inactivation of 99.99% of microorganisms) is guaranteed. The efficiency can be seen as the amount of water that can be disinfected by a certain amount of electric power. This efficiency influences the running costs of a plant. The running costs result mainly from the electric power consumption of the plant and the costs for lamps which have to be exchanged, which for low pressure lamps nowadays is approximately every 10,000 hours.

In the 1970s a first attempt was undertaken to enhance UV efficiency by proposing amalgam low pressure high-output UV (ALPHO) lamps (Franck 1971, 1973; Bloem *et al.* 1977) as an alternative to low-pressure mercury lamps. The mercury vapour pressure within the ALPHO lamp is regulated to optimal values by attaching an amalgam of mercury and metals such as bismuth, indium, lead, tin or others (e.g. Lankhorst & Niemann 2000; Lankhorst *et al.* 2000) to the inside wall of the lamp's quartz envelope. This allows lamp operation at higher input power, gaining higher UV emittance by maintaining relatively high electrical-to-germicidal power conversion efficiency (Heering 2004). The latest improvement of lamps has been the introduction of a protective coating (e.g. Vasils'ev *et al.* 2006) based on aluminum oxide on the inner side of the quartz tube that prolongs lifetime significantly (e.g. Schalk *et al.* 2006) and emission to a certain extent. At the beginning, an inductive ballast, ignitor and eventually a heating transformer were necessary for each lamp. Nowadays, one electronic ballast provides optimal power conditions to multiple lamps.

A frequently used measure to describe the power efficiency of a UV disinfection lamp is the efficiency in converting electrical power into UV radiation. There are several terms in use for this, such as electrical-to-germicidal power conversion efficiency or UV-C 254 nm lamp efficiency. It is simply the ratio of the electric power consumption of the lamp (expressed in watts) and the UV-C output of the lamp (expressed in watts). It is expressed in units of percent. A standard method for measuring this quantity for low pressure UV lamps was proposed by the IUVA Manufacturer's Council several years ago (Lawal *et al.* 2008). However, inside a UV disinfection plant the UV emittance is influenced slightly by the temperature of the water (e.g. Schmalwieser *et al.* 2015) but more by lamp aging (e.g. Schmalwieser *et al.* 2014, 2015), which is accounted by the biodosimetric test. Sleeve fouling may also influence the efficiency but can be mostly avoided by proper maintenance (e.g. wiper system).

The disinfection capability depends strongly on the hydrodynamic transport of the microorganism through the UV chamber, which is influenced by the flow field and chamber geometry (Schoenen *et al.* 1993; Chiu *et al.* 1999a). In the late 1990s computational fluid dynamics software packages were developed to model and to optimize UV water disinfection chambers (e.g. Chiu *et al.* 1999b) to optimize the UV disinfection performance by effective design (e.g. Bakker *et al.* 2001). Improvement of modeling is still ongoing (e.g. Xu *et al.* 2015). Nowadays, baffle systems inside the chamber are used to optimize hydrodynamic conditions, guiding the microorganisms more effectively through the radiation field.

Until now, a comparison of the power efficiency of plants has not been a simple task as there are several influencing parameters which have to be taken into account. The smallest plants contain one lamp and disinfect a few cubic meters of water per hour while the largest contain hundreds of lamps and disinfect thousands of cubic meters per hour (e.g. Schmalwieser *et al.* 2015). Some plants can disinfect low UV transmissive water while others need water with higher UV transmission (UVT). Even if transmission range and amount of disinfected water are similar, plants may differ in the number of lamps and power of lamps.

In this paper we describe the method to calculate the power efficiency and apply this to different low pressure UV disinfection plants for drinking water which fulfil the requirements according the same standard, in our case the Austrian standard ÖNORM M5873-1. Further on we identify those parameters that influence the power efficiency.

The results provide helpful information, about the effective usage of electric power by operating a UV disinfection plant for drinking water in water works.

MATERIALS AND METHODS

As stated above, the power efficiency of a plant can be seen as the amount of water that can be disinfected (99.99% inactivation) by a certain amount of electric power. The amount of disinfected water depends on the UVT of the water. The amount of water which can be disinfected by a plant in dependence of the UVT of the water is nowadays determined by standardized biodosimetric test procedures, like ÖNORM M5873-1, which prove worst-case scenarios in respect of later application. Such a test defines the permissible operating range, which is the maximum permissible flow in dependence of the UVT of the water. The electric power consumption of a plant can be measured.

Permissible flow rate in dependence of transmission

Nowadays standardized biodosimetric test procedures require a minimum UV disinfection dose under any condition and examine the worst-case scenario. For this, lamps at the end of their lives are assumed. The plants are tested at different flow rates and different UVT, which lead to a couple of test points. At each test point, calibrated biodosimeters (like *bac. sub.* spores) are added to the water, UV irradiance is measured in parallel and the survival after the biodosimeters have passed is observed. From this one gets the reduction equivalent fluence in dependence of transmission and flow rate. As the distance between this test points is not too large, one can assume steadiness. An analytical function can be fitted to interpolate values between the test points that are normalized to a joint reduction equivalent fluence, in our case 400 J/m². With that one gets an analytical formula that enables the calculation of the permissible flow rate in dependence of UVT within the lowest and the highest transmissions that were tested.

This final result of the biodosimetric test is called the permissible operating range, which states the maximum flow Q in dependence of UVT. It should be noted that for low pressure plants the UVT is measured at 254 nm. The reference path length for measurements of UVT in drinking water is 100 mm (UVT_{10mm}). Several standards demand a minimum path length for measurements of 40 mm (e.g. ÖNORM 5873-1). However UVT is often given for a path length of 10 mm (UVT_{10mm}). Therefore UVT_{10mm} are given in this paper as well.

The permissible operating range takes into account the reduced emission at the end of lamp life and generally a safety factor for measurement uncertainties as from the UV radiometer. The permissible operating range of a disinfection plant must be delivered to the operator of the plant. In Figure 1 an example of a permissible operating range is shown. The filled circles indicate the lowest and the highest test points, the empty circles indicate other test points. Here the straight line denotes the maximum permissible flow and the hatched area the permissible operating range. In this example the plant may not be operated when UVT_{100mm} is lower than 10% (UVT_{10mm} <79.4%) and there may be no higher flow than 7 even when UVT_{10mm} is higher than 80% (UVT_{10mm} >97.8%) as this was the highest test point.

Electrical power consumption

The electric power consumption of a UV disinfection plant includes electric power for lamp(s), ballast(s), control and monitoring units, display device, UV radiometer and fan(s) for the electrical cabinet. It does not include electric power for the pumps and for flow regulation. High quality test centres like WTWt (Sommer *et al.* 2014) provide these values from measurements during the biodosimetric test.

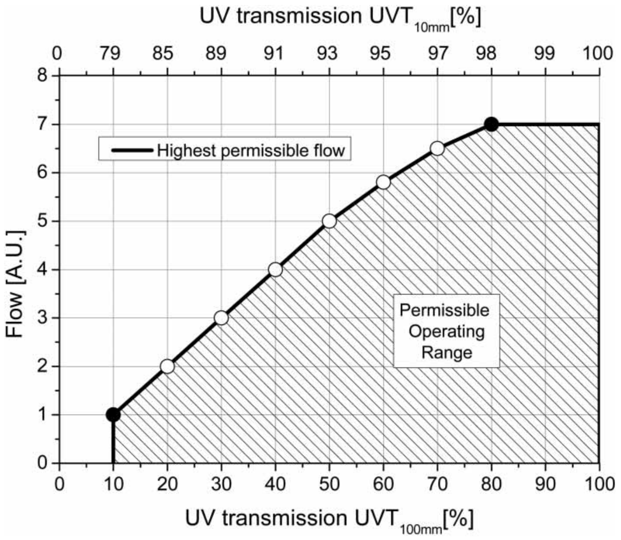

Figure 1 | Example visualization of a permissible operating range.

The determination of supply voltage and supply current(s) has to be carried out by means of electric power monitoring devices with a true root-mean-square measurement (TRMS). The electric power consumption (active power) is also measured by the TRMS method of an electric power monitoring device. Measured values are recorded by an electronic data acquisition system including a measurement software package.

Calculation of specific power consumption

The specific power consumption (SPC) is defined here as the measure of power efficiency. The SPC is the electrical power consumption P which is necessary to disinfect 1 m^3 of water with a certain UVT by a determined minimum reduction equivalent fluence. It can be calculated as the ratio of the electrical power consumption P expressed in watts and the maximum flow Q(UVT) in dependence of UVT expressed in m^3 per hour:

$$\mathrm{SPC(UVT)} = \frac{P}{\mathrm{Q(UVT)}}$$

The SPC(UVT) is expressed in units of Wh/m^3. The maximum flow rate Q(UVT) is given in the manual, because it is essential for the operator. It is generally provided as an analytical formula that enables the calculation of Q(UVT) for any UVT within the operating range and is tabulated. The selection criterion for the plants was the availability of reliable values of electrical power consumption P.

Selection of UV disinfection plants for application

The SPC will be calculated here for UV disinfection plants that were all tested under the same protocol. For this we selected low pressure UV disinfection plants for drinking water tested according to ÖNORM M5873-1. Plants in accordance with this standard ensure a minimal reduction equivalent fluence of 400 J/m^2. In accordance with ÖNORM M5873-1 the UVT refers to a path length of 100 mm, further referred to as $\mathrm{UVT_{100mm}}$. Additionally the transmission is given for a path length of 10 mm, further referred to as $\mathrm{UVT_{10mm}}$. The selection criteria were: the plant passed the ÖNORM test successfully, the test was done within the past 10 years, the permissible operating range is known, Q(UVT) can be calculated, and a reliable value of the electric power consumption is available.

Costs for lamps and electrical power

The running costs of a disinfection plant result from electrical power consumption, exchanging of lamps, repair and maintenance. Knowing the SPC(UVT) of a plant in advance makes it possible to estimate the running costs, which may be an important buying criterion. In the following, we show how to estimate the costs for 1 m^3 of water, C including the costs for electric power consumption C_P, costs for the lamps C_L and cost for a periodic service C_S.

$$C = C_\mathrm{L} + C_\mathrm{P} + C_\mathrm{S}$$

The manufacturers guarantee a certain lifetime for the lamps. The costs per hour for the lamp, C_L, can be approximated by the product of the number of lamps n and the price for one lamp p divided by the guaranteed lifetime T_L (expressed in hours):

$$C_\mathrm{L} = n * \frac{p}{T_\mathrm{L}}$$

If a periodic service is arranged, the price of one service p_S can be broken down by the period T_S between services on an hourly basis. The cost C_S is:

$$C_\mathrm{S} = \frac{p_\mathrm{S}}{T_\mathrm{S}}$$

The amount of water that can be disinfected within this hour depends on the SPC(UVT) of the plant. The price P(UVT) for 1 m^3 depends on UVT and is:

$$\mathrm{P(UVT)} = \frac{C}{\mathrm{SPC(UVT)}}$$

If the plant will run on a constant water flow rate the corresponding SPC(UVT) must be selected. If transmission changes, the SPC(UVT) of the highest UVT and the lowest UVT deliver a range for costs.

RESULTS AND DISCUSSION

Selected low pressure UV disinfection plants for drinking water for application

Using the above selection criteria, 63 UV disinfection plants for application could be found. These plants were produced by 13 different manufacturers out of nine countries. These plants are equipped with from one up to 21 lamps, with 60% having four lamps or less and 15% have more than ten lamps. Electrical power consumption of the lamps ranges from 41 W to 560 W (median 235 W). The lamps were produced by nine different manufacturers. However this number is not certain because most plant manufacturers mark the lamp with their own brand name and do not provide further information about lamp origin.

The UV-C efficiency of a lamp is the ratio of the UV-C output of the lamp and the electric power of the lamp both expressed in units of watts. The UV-C efficiency is either given by the manufacturer or can be calculated if both values are given. The UV-C output is not provided by all manufacturers or manuals. Given or calculated values of UV-C efficiency varied between 0.31 and 0.41.

The electrical power consumption of UV disinfection plants was found to be within 47 W and 13 kW (median 695 W). Water flow rate spanned a wide range from 0.9 m^3/h up to 1,549 m^3/h.

Plants are designed for UVT_{100mm} ranging from 2.5% up to 90% (UVT_{10mm}: 69% to 99%) whereas all plants can work in the range from 30% to 60% (UVT_{10mm}: 88% to 95%). Only a few plants can disinfect water at $T_{100mm} \leq 5\%$. The most common operating range in UVT_{100mm} is from 10.7% to 82%, which corresponds to 80% and 98% for a path length of 10 mm.

As stated above, the end of lamp life is expressed as relative irradiance compared to irradiance from a new lamp (new lamp = 100 h). The end of lamp life irradiance was within 65% and 85% (median = 80%). The given lifetime expectations of lamps ranged from 9,000 hours up to 16,000 hours.

Power efficiency and UVT of the water

The power efficiency, expressed as the specific power consumption SPC(UVT), was calculated over the permissible operating range for each plant. The lowest UVT_{100mm} was 2.5% ($UVT_{10mm} = 69\%$); 62% of the plants can disinfect water with $UVT_{100mm} = 10\%$ ($UVT_{10mm} = 79\%$) or higher. From these, the median SPC(UVT) was calculated, and the highest and the lowest SPC(UVT) values were looked for. The SPC(UVT) of all plants for distinct transmissions are depicted in Figure 2. Medians and extreme values are listed in Table 1. It can be seen

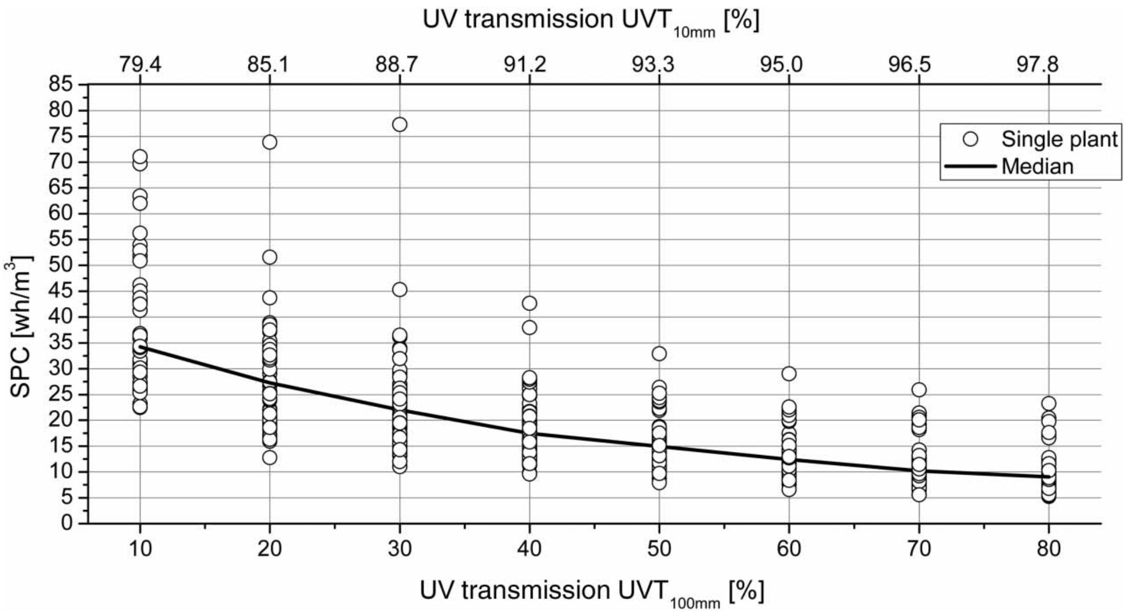

Figure 2 | SPC depending on UVT (at 254 nm) of 63 plants for a reduction equivalent fluence of 400 J/m². The black line indicates the median value.

that SPC values increase exponentially (indicated by the median in Figure 2) with decreasing transmission and that there is a broad range of variation. As can be seen from the third column (Min) of Table 1, for high transmissive water ($UVT_{100mm} = 80\%$) the SPC is at least 5.3 Wh/m^3. If $UVT_{100mm} = 50\%$ it is at least 7.9 Wh/m^3 and at least 22 Wh/m^3 for $UVT_{100mm} = 10\%$. The highest values (column 5, Max) are 71 Wh/m^3 for $UVT_{100mm} = 10\%$, 33 Wh/m^3 for $UVT_{100mm} = 50\%$ and 23 Wh/m^3 for $UVT_{100mm} = 80\%$, with those being 3.2, 4.2 and 4.4 times higher than the lowest values.

It can also be seen that the most effective plant can disinfect a greater amount of water with $UVT_{100mm} = 10\%$ (SPC = 22 Wh/m^3) than the worst when water has an $UVT_{100mm} = 80\%$ (SPC = 23 Wh/m^3) by consuming the same electrical power. In Figure 2 two outliers can be recognized: one plant at $UVT_{100mm} = 20\%$ for which $SPC(UVT_{100mm} = 20\%)$ is 5.8 times higher than the lowest and another plant at $UVT_{100mm} = 30\%$ for which $SPC(UVT_{100mm} = 30\%)$ is 7.0 times higher than the lowest. It should be mentioned that $T_{100mm} = 20\%$ and 30% are the lowest permissible transmissions for both plants. At $UVT_{100mm} = 50\%$ the SPC of both plants is within those of the other plants. This clearly indicates that plants may become ineffective at the limits of the permissible operating range and that operating at these conditions should be avoided in respect of power efficiency.

Power efficiency and number of lamps

The SPC of plants was analysed in respect of the number of lamps inside. Theoretically one could assume that the more lamps are inside a disinfection chamber, the more uniform would be the distribution of fluence and with that the more effective would be the plant. On the other hand a plant with one lamp only should be most easy to optimize, because the radiation field is not influenced by absorption and reflection of other lamps and sleeves and only one sleeve may disturb the water flow.

The SPC of plants in respect of the number of lamps inside is visualized in Figure 3 and Table 2 for distinct UVT, and delivers the following insights.

Less effective are plants with one lamp. For these plants the lowest SPC (SPC_{min}) is 10 Wh/m^3 at $UVT_{100mm} = 80\%$ (Figure 3, empty circles, Table 2 col. 7), 13 Wh/m^3 at $UVT_{100mm} = 50\%$ (Figure 3, filled circles) and 36 Wh/m^3 at $UVT_{100mm} = 10\%$ (Figure 3, empty triangles, Table 2 col. 4). For plants with two lamps the values are almost identical: $SPC_{min}(UVT_{100} = 80\%) = 10$ Wh/m^3, $SPC(UVT_{100} = 50\%) = 14$ Wh/m^3, $SPC(UVT_{100} = 10\%) = 34$ Wh/m^3. Higher effectiveness is gained by plants with three lamps or more especially at medium (filled circles) and high (open circles) UVT of drinking water. The SPC_{min} at $UVT_{100mm} = 80\%$ decreases to a value of 5 Wh/m^3 and to 10 Wh/m^3 at $UVT_{100mm} = 50\%$. For low UVT (open triangles, $UVT_{100mm} = 10\%$, $UVT_{10mm} = 79\%$) the increase in efficiency is less as the SPC_{min} found is 29 Wh/m^3. Even for a plant with 18 lamps the SPC_{min} at $UVT_{100mm} = 10\%$ is around 30 Wh/m^3. This makes obvious that low transmission is a challenge for all types of plants.

Power efficiency and application range

UVT of the water and the amount of drinking water needed are the selection criteria (application range) for a plant.

Table 1 | SPC depending on UVT of the water at 254 nm

UVT	UVT	SPC			
UVT_{100mm} [%]	UVT_{10mm} [%]	Min [Wh/m^3]	Median [Wh/m^3]	Max [Wh/m^3]	Max/Min [1]
10	79.4	22	34	71	3.2
20	85.1	13	27	74	5.8
30	88.7	11	22	77	7.0
40	91.2	9.6	17	43	4.4
50	93.3	7.9	14	33	4.1
60	95.0	6.6	12	29	4.4
70	96.5	5.6	10	26	4.7
80	97.8	5.3	9.0	23	4.4

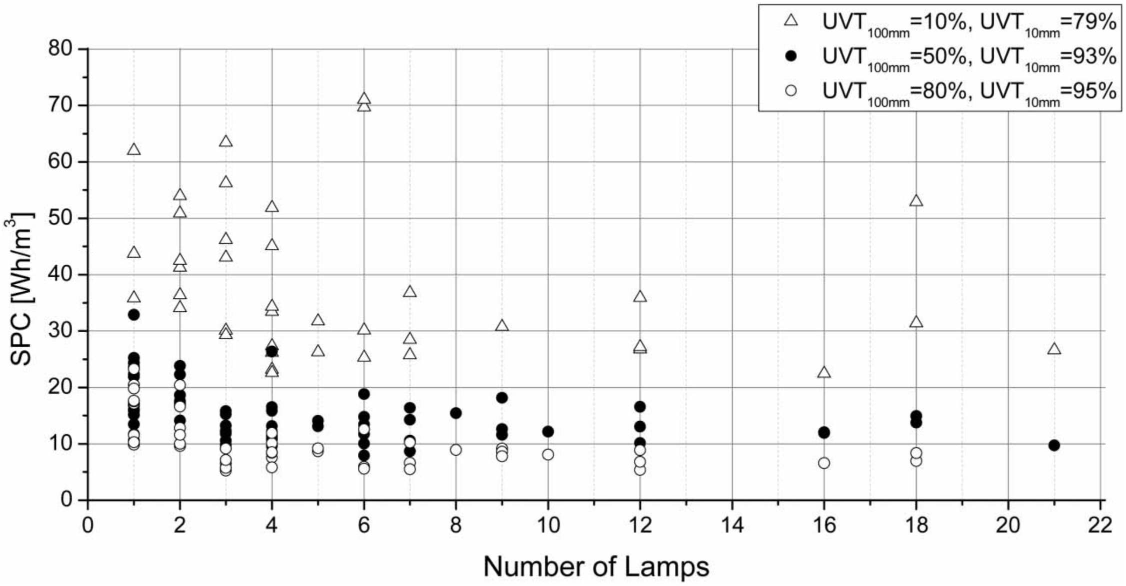

Figure 3 | SPC (for a reduction equivalent fluence of 400 J/m^2) as a function of numbers of lamps for different UVT at 254 nm (SPC values for ≥15 lamps are summarized and indicated by +15).

Table 2 | Application range of plants (Q, UVT) with different numbers of lamps and the lowest SPC (SPC_{min}) for a reduction equivalent fluence of 400 J/m^2

	UVT_{100mm} = 10% (UVT_{10mm} = 79%)			**T_{100mm} = 80% (UVT_{10mm} = 98%)**		
Number of lamps	**Q_{min} [m³/hr]**	**Q_{max} [m³/hr]**	**SPC_{min} [Wh/m³]**	**Q_{min} [m³/hr]**	**Q_{max} [m³/hr]**	**SPC_{min} [Wh/m³]**
1	0.86	9.1	36	2.7	33	10
2	5.6	15	34	25	54	10
3	4.4	82	29	35	182	5.3
4	9.1	70	23	30	280	5.8
5–9	11	208	25	34	499	5.5
≥10	30	460	22	479	720	5.3

However there is no certain plant type for certain criteria. In the following short overview of plants in respect of the number of lamps inside, UVT and flow rate of water are given. Table 2 summarizes the application ranges (highest permissible flow Q_{max} and lowest Q_{min}) of plants for different numbers of lamps for T_{100mm} = 10% and T_{100mm} = 80% as well as the lowest SPC which was found.

The smallest plants, plants with one lamp, consume electrical power between 47 W up to 346 W and are typically (70% of these) designed for UVT_{100mm} between 20% and 82%. A few plants (from our sample) may work also when UVT_{100mm} is 10% and one plant when UVT_{100mm} = 4%. The permissible flow rates at the lowest UVT are between 0.86 m^3/h and 9.1 m^3/h and between 2.7 m^3/h and 34 m^3/h at highest UVT. If water with UVT_{100mm} = 4% (UVT_{10mm} = 72.5%) has to be disinfected, the only available plant (in our sample) has a SPC of 62 Wh/m^3. If UVT_{100mm} = 10% the lowest SPC decreases to 36 Wh/m^3. At UVT_{100mm} = 80% (UVT_{10mm} = 98%) the lowest SPC is 10 Wh/m^3.

Plants with two lamps (312 W up to 925 W) are typically (six from seven) designed to disinfect water also with UVT_{100mm} = 10%. Two plants can even work at UVT_{100mm} = 4%. Permissible flow rates are higher than for plants with one lamp (at lowest transmission: 5.6 m^3/h up to 15 m^3/h; at highest transmission: 25 m^3/h up to 72 m^3/h).

Plants equipped with three or four (250 W up to 1,390 W, 248 W up to 2,141 W) are all used for water with $UVT_{100mm} \geq$ 10% and higher flows (4.5 m^3/h up to 26 m^3/h and 36 m^3/h up to 192 m^3/h; 9 m^3/h up to 70 m^3/h and 30 m^3/h up to 346 m^3/h).

Beside some exceptions, plants with five and more lamps are generally applied for $UVT_{100mm} \geq$ 10% (50% of plants) or $UVT_{100mm} \geq$ 20% (40% of plants).

Further we have estimated the minimum electric power which is at least necessary to disinfect a certain amount of drinking water possessing a certain UVT. For this, the minimum SPC (SPC_{min}) gained above (Table 2) were used. The result is depicted in Figure 4 for UVT_{100mm} of 10% (Figure 4(a)) and 80% (Figure 4(b)) respectively for UVT_{10mm} of 79% and 98%. In this figure the line between the symbols indicates the minimum electric power consumption in dependence of water flow for a certain quantity of lamps. It becomes obvious that selecting a plant with more lamps can save power. For example, in Figure 4(a) it can be seen that if a flow of 5 m³/h or more at UVT_{100mm} of 10% is needed then a plant with three lamps (line connecting triangles) needs less electric power than a lamp with one (line connecting squares) or a plant with two lamps (dotted line connecting squares). In Figure 4(b) it can be seen that savings

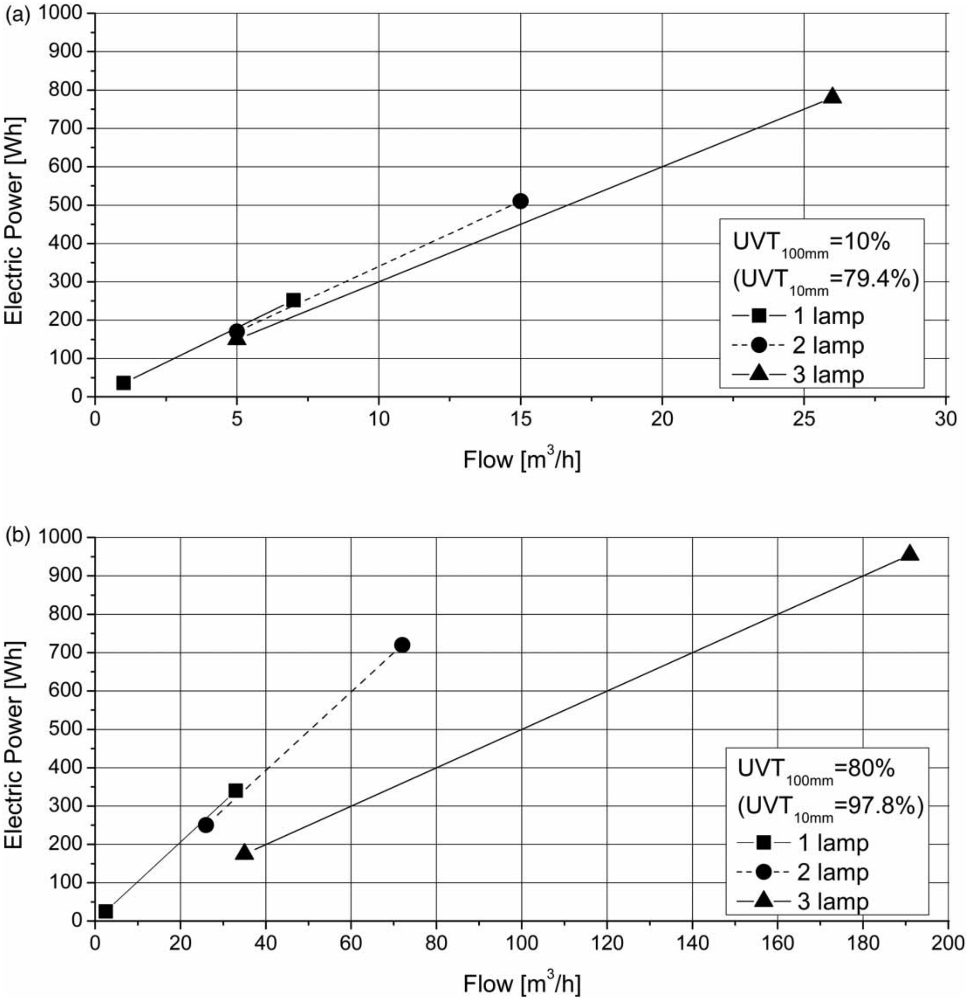

Figure 4 | (a) Minimum electrical power needed to disinfect a certain amount of drinking water (flow) at a reduction equivalent fluence of 400 J/m^2 for different plant sizes (number of lamps) and water transmissions of $UVT_{100mm} = 10\%$. (b) Minimum electrical power needed to disinfect a certain amount of drinking water (flow) at a reduction equivalent fluence of 400 J/m^2 for different plant sizes (number of lamps) and water transmissions of $UVT_{100mm} = 80\%$.

are higher at $UVT_{100mm} = 80\%$. If a flow of 40 m^3/h or more is needed then a plant with three lamps (line connecting triangles) needs approximately half of the electric power that a plant with two lamps does. It should be noted that the initial cost for a plant with more lamps may be higher.

Power efficiency, manufacturer and year of certification

The SPC was analysed also in respect of the manufacturer to see if a certain company uses more advanced technology for plant design then others. We could not identify manufacturers that produce more effective UV disinfection plants than other ones. However plants from different manufacturers are not directly comparable as some focus more on small plants, or more on less transmissive water than others.

We analysed the SPC also in respect of the year of certification. No improvement of the SPC over time could be found. This can be explained by the fact that all plants are equipped with ALPHO lamps and that manufacturers design their new plants for new application ranges.

Costs for lamps and electrical power

The following simplified example cost estimate was done using prices valid in Austria in 2016 including electric power consumption and exchange of lamps only. Nowadays, manufacturers guarantee a lifetime of lamps on the order of 10,000 hours or even more. The price for a 100 W lamp is approximately 100 euro. This denotes a cost of 0.010 euro per hour for a 100 W lamp through aging. The price for 1 kWh of electric power is roughly 0.13 euro. With that, the operating of a 100 W lamp results in a power cost of 0.013 euro/hour. In sum one gets running costs of 0.023 euro/hour.

The amount of water that can be disinfected within this hour depends on the SPC of the plant. Using the SPC values from above, with such a plant, drinking water between 13 m^3 ($SPC = 7.9\ Wh/m^3$) and 3 m^3 ($SPC = 33\ Wh/m^3$) per hour can be disinfected if $UVT_{100mm} = 50\%$ ($UVT_{10mm} = 93\%$) whereas the costs are 0.013 euro (power) and 0.010 euro (lamp). Apportioning this to 1 m^3, the costs would be from 0.00103 to 0.00429 euro for electric power and 0.00079 up to 0.0033 euro for the lamp. In total, costs arise between 0.00182 and 0.00759 Euro for the disinfection of 1 m^3 drinking water.

CONCLUSION

Our study has shown that nowadays UV disinfection plants can be very effective. With electrical power of 1 kW an amount of up to 182 m^3 water per hour can be disinfected at $UVT_{100mm} = 80\%$ ($SPC = 5.5\ Wh/m^3$), up to 130 m^3 at $UVT_{100mm} = 50\%$ ($SPC = 7.7\ Wh/m^3$) and up to 44 m^3 at $UVT_{100mm} = 10\%$ ($SPC = 23\ Wh/m^3$).

It became obvious that the UVT of the water strongly influences SPC, as the lower the transmission, the higher is the SPC. The SPC increases exponentially with decreasing transmission. A small underestimation of transmission may lead to a relatively high loss in power efficiency. Therefore it is essential to know the UVT range of the water source before selecting or establishing a plant.

It was further shown that there is a large variation in SPC. There are several causes for this. First of all there are differences in the efficiency of converting electric power into UV-C emittance by the lamp. The ratios of UV-C power to nominal electric power of the lamp were found to be in the range from 0.31 to 0.41. With that the power efficiency may vary by 25%. The transmission of protective quartz sleeves was not always specified but, when stated, it was between 0.8 and 0.9. Another influence is the emission at the end of lamp life because the permissible flow rate is valid until this time point. This means that the permissible flow is calculated for the end of lamp life. Manufacturers have defined the end of life of lamps with values between 65% and 85% from initial emittance. A comparably small contribution to the variations comes from the measurement uncertainty of the plant radiometer for which the permissible flow rate is reduced. The Austrian standard sets a minimum measurement uncertainty of at least 15% for the plant radiometer. This uncertainty is also increased by the temperature drift of the sensor for the specified temperature range. The temperature drift is up to 6% for the temperature range from 0 °C to 40 °C. Additionally the measurement uncertainty of the plant radiometer determined during the biodosimetric test is added, which is below 10% in all plant radiometers. According to the standard the total uncertainty is the root of the square sum of those three uncertainties. Finally, the total measuring uncertainty of the sensors is between 16% and 19%. This leads also only to a small variation in the SPC. Taking these factors into account (0.31–0.41, 0.8–0.9, 0.65–0.85, 0.81–0.86) the SPC of plants could differ by a factor of 2.0 independent of UVT, which is clearly less than the observed range from 3.2 to 7.0 (Table 1, column 5). From this we conclude that the hydraulic conditions inside the irradiation chamber have an important contribution to the differences in SPC.

A careful selection of a plant on the basis of the SPC can help to hold the running costs of the plant low, specifically the production costs for drinking water. Furthermore, electrical power is related to CO_2 production, another reason for low SPC values.

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First received 22 July 2016; accepted in revised form 31 October 2016. Available online 5 December 2016