J Water SRT — Aqua Vol. 48, No. 4, pp. 154–160, 1999

Description and application of biodosimetry—a testing procedure for UV systems

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ABSTRACT: Biodosimetry is a new testing procedure for UV systems used to disinfect water. It is the first standardised test method for such systems that has been proven in test stand comparison with respect to practicality and reproducibility. The method is unique in that the reactor geometry and the different types of UV lamps are objectively incorporated into the determination of the microbiological performance. All results that follow this report are the result of practical experiments with the biodosimetry: test between two laboratories, the comparison of different reactor design and different types of UV lamps.

INTRODUCTION

Water disinfection using ultraviolet (UV) radiation is becoming increasingly popular relative to more traditional methods involving chlorine and chlorine dioxide. The only hurdle standing in the way of its ultimate breakthrough is the lack of a standardised test procedure. Such a standard would enable customers to objectively compare different UV systems. The various analyses performed to date suffer from a discrepancy between the theoretically calculated UV dose and the experimentally determined kill rate [1–4]. The problem lies in the application of different mathematical models and the difficulties in incorporating the flow dynamics into these models [5,6]. Determining the disinfection performance of UV systems is complicated by the lack of a standardised microbiological test procedure and the lack of a measuring system with which to measure the UV dose in a flow-through UV system. This situation is unsatisfactory for both health authorities and customers since it prevents the comparison of the disinfection performance of different reactor designs and irradiation chambers.

Biodosimetry was developed as a result of a research and development project conducted by Heinz Bernhardt from 1987 to 1993 [3]. The Biodosimetry eliminates these deficiencies and has been used as the basis for UV system test procedures [7–9]. The German DVGW Standard W 294 (10/97) [10] and the Austrian standard ÖNORM M 5873 (2/96) [11] for testing UV systems have been issued. Biodosimetry is characterised by the use of a calibration curve of the UV sensitivity of a test organism in relation to the UV dose to determine the disinfection potential of a given UV system. In this paper the most important parameters and their influence on the disinfection performance are described. This information helps to understand the fundamentals of Biodosimetry and the test procedure. The influence of the reactor geometry on the disinfection performance is shown in the applications of Biodosimetry.

SIZING OF PRACTICAL UV SYSTEMS

Sizing UV systems to the microbiological requirements of the customer essentially depends on three parameters:

- the flow rate (m^3/h);
- the UV transmission of the water at a wavelength of 254 nm; and
- the microbiological requirements which determine the UV dose, for example drinking water standards, food and drink industry standards, or ultra pure water standards.

Furthermore, the unique requirements of each customer and their particular application must be met.

The three parameters can be related to each other by a principle sizing curve like the one shown in Fig. 1 where flow rate is plotted against UV transmission of the water at 254 nm. The sizing curve represents the constant UV dose needed to meet the microbiological requirements of the water quality at

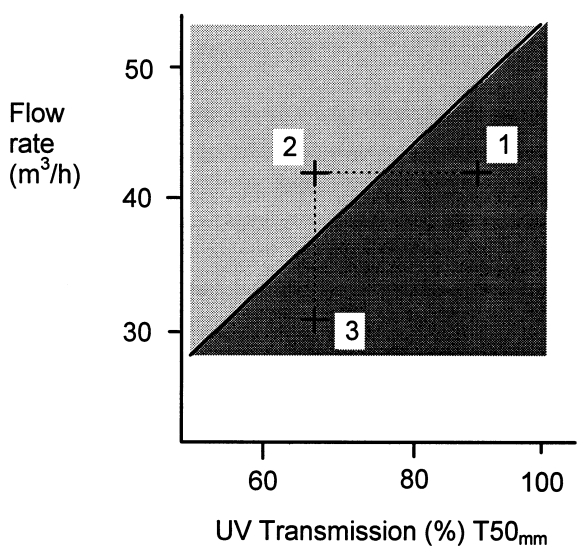

Fig. 1 Sizing curve of a UV unit.

the end of the useful service life of the lamp. The area under the sizing curve represents the operating range for the system in which chosen the operating point (1) of the UV system must lie. Above the sizing curve the high flow rate, which results in a decreased residence time in the irradiation chamber, and/or the low transmission of the water cause the UV dose to be too low. Weathering effects, for example, can cause fluctuations in the UV transmission of water depending on the filtration performance of the ground, shifting the operating point from (1) to (2). The UV monitoring system recognises this shift and activates the appropriate alarm. In order to ensure that the supply of disinfected water is nevertheless continued, the UV system shifts the operating point from the 'red' zone into the 'green' zone at point (3) by decreasing the flow rate. This can be achieved to a certain extent by the deactivation of a supply pump or the appropriate setting of flow rates using valves.

In practice, transmission fluctuations are the most common reason for the unsatisfactory performance of UV systems. Frequently a defect in the UV system is suspected because the sensor system operates at a wavelength invisible to the human eye and thus no apparent change in the clarity of the water occurs to indicate a problem. Thus, a system should be designed to cope with the lowest expected level of transmission, although rarely occurring extreme values should not lead to over-sizing of the UV system. This requires that a high level of knowledge and experience are applied to the design of a system.

MEASURING DISINFECTION PERFORMANCE: BIODOSIMETRY

Laboratory irradiation unit

The laboratory irradiation unit shown in Fig. 2 is used to determine the UV sensitivity of test organisms. The spore form of *B. subtilis* ATCC 6633 is used as the test organism. Use of spores to test the disinfection performance of a UV unit offers distinct advantages over the use of live organisms. The spores have the important property that their UV sensitivity remains constant from the time they are retrieved from the incubator until the actual test. Furthermore, spores proliferate in large numbers for testing units with high flow rates, and test spores can be stored for some time.

Fig. 2 Laboratory irradiation unit.

A dose–response curve is determined as follows: A suspension of *B. subtilis* spores is distributed into numerous Petri dishes. Each Petri dish is subsequently irradiated to various levels of exposure. The radiant exposure is measured in J/m^2 or $W{\cdot}s/m^2$. The radiation measurement comprises the irradiance (W/m^2) and the exposure time in seconds as recorded by a reference sensor. The irradiation conditions are varied in that the individual Petri dishes are exposed to a constant irradiance for varying lengths of time. Following exposure, the samples are prepared for incubation by a series of dilutions. After a 48-h incubation period the colony count is performed. Only those dilutions containing between 30 and 300 colonies are included in the evaluation of the test.

Since the spore suspensions in the Petri dishes are not agitated during the test, the laboratory irradiation unit is described as a static system. The advantage of such a static system is that the dose–response curve, such as the one shown in Fig. 5, for a test organism is a reproducible linear function between the kill rate and the radiant exposure over a wide range (between approx. 200 and 800 J/m^2). This permits the dose–response curve to be used as a reference against which future spore series intended for the testing of UV systems can be compared. If the dose–response curve of a spore series lies within a set of tolerances given for the slope and the radiant exposure range, the series can be used for tests of UV systems on a UV test stand.

UV test apparatus

The greatest expenditure in the testing of UV systems is the construction of a dedicated test apparatus with the required water supply and disposal system. The test apparatus of the Austrian Federal Research and Testing Center Arsenal in Vienna and of Katadyn Products Inc. in Wallisellen are shown in Fig. 3 and 4, respectively. These test stands, with which all the biodosimetric tests to date have been performed, were constructed in accordance with standardised UV system test procedures. Since neither practical experience nor data have been collected using DVGW Standard W 294, the experimental procedure is based on ÖNORM M 5873.

The UV systems to be tested are called dynamic systems because the spore-contaminated water streams flow through the irradiation zone in complex patterns. The mathematical modelling of these flow patterns and the radiant exposure (J/m^2) gives rise to an expected disinfection performance which must then be confirmed with Biodosimetry.

The UV system to be tested is installed in the test apparatus according to the standardised test procedure and the relevant

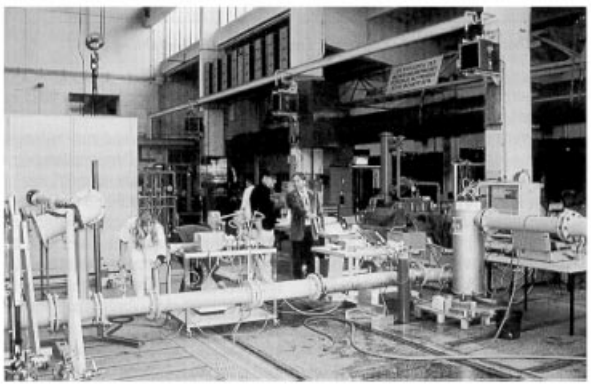

Fig. 3 Test apparatus at the Austrian Federal Research and Testing Center Arsenal in Vienna.

Fig. 4 Test apparatus at Katadyn Products Inc. in Wallisellen/Zürich.

experimental parameters are set (flow rate, transmission stimulated by the addition of sodium thiosulphate, UV lamp intensities reduced to the intensity level at the end of its service life). The spore suspension is added to the water in a static mixer in the test apparatus and then flows through a relaxation zone into the UV system. 'before UV' water samples are extracted before a 90° elbow immediately upstream of the unit, as required by the test standard. The 'after UV' water samples are taken after a static mixer which is installed just downstream of the of the unit. Sampling is not performed at points in the UV system to prevent possible errors.

In accordance with ÖNORM M 5873, five samples, each before and after of the UV unit, are taken and each sample is analysed twice. The water flow is temporarily stopped and the UV system is shut down before the whole sampling procedure with the running system is performed a second time. An additional 'before UV' sample is taken as the source suspension for the determination of a dose–response curve using the laboratory irradiation unit. This serves to check if and how much the UV sensitivity of the test organism changes during the tests.

Key element of biodosimetry: determination of the radiant exposure (J/m^2)

To date the testing of UV systems has been performed with test organisms of varying UV sensitivities. The resulting lack of uniform test conditions and reference data prevents the different measurements from being compared. The new and unique feature of Biodosimetry is the use of a standardised procedure in which the dose–response curve is used as a reference curve. The kill rate determined from the dynamic experiment on the test stand with a UV system running at some set of operating parameters is then correlated with the radiant exposure in J/m^2 that was required to achieve that kill rate on the reference curve, as shown in Fig. 5.

On the left side in Fig. 5 the principle of a sizing curve as an example is shown. At the same time the testing parameters of a measuring point of the calculated sizing curve which has to be checked bidosimetrically, are explained: flow rate (m^3/h), simulation of the UV transmission at the wavelength of 254 nm and the reduced power of UV lamp for simulating the UV intensity at the end of the service life time of a UV lamp. The description in the middle contains the sampling procedure of the UV unit which is installed in the test stand. The water samples before and after the UV unit are taken at one measuring point. The results of the samples between before and after the UV unit follow a factor of the reduction of the test germ. The graph on the right side describes the final step of determination of the UV dose. The factor of reduction, i.e. 1.7, corresponds to a UV dose of 400 J/m^2, which is given from the dose response curve. This curve was determined with the laboratory irradiation unit. When the reduction factor is for instance 3.0, then the UV dose would be 600 J/m^2.

The whole procedure is repeated with a total of four sets of operating parameters differing in flow rate, transmission of the water, and UV lamp intensity. The four data points constitute the reference performance curve for the entire operating range of the UV system. This curve, which represents the line of constant UV dose, is also the sizing curve for the practical use of the given UV system.

MONITORING THE DISINFECTION PERFORMANCE: A NEW SENSOR SYSTEM

Health authorities have repeatedly pointed out the lack of comparability between online monitoring data and the actual disinfection performance of UV systems in practical applications. On the one hand the sizing of UV systems depends on a variety of theoretical models, and on the other hand each manufacturer uses a different sensor system to monitor the disinfection process.

As a solution to this problem, test procedures DVGW Standard W 294 and ÖNORM M 5873 outline a new sensor system with which it disallows any adjustment of the data display (sensor signal). Finally the display has been given a

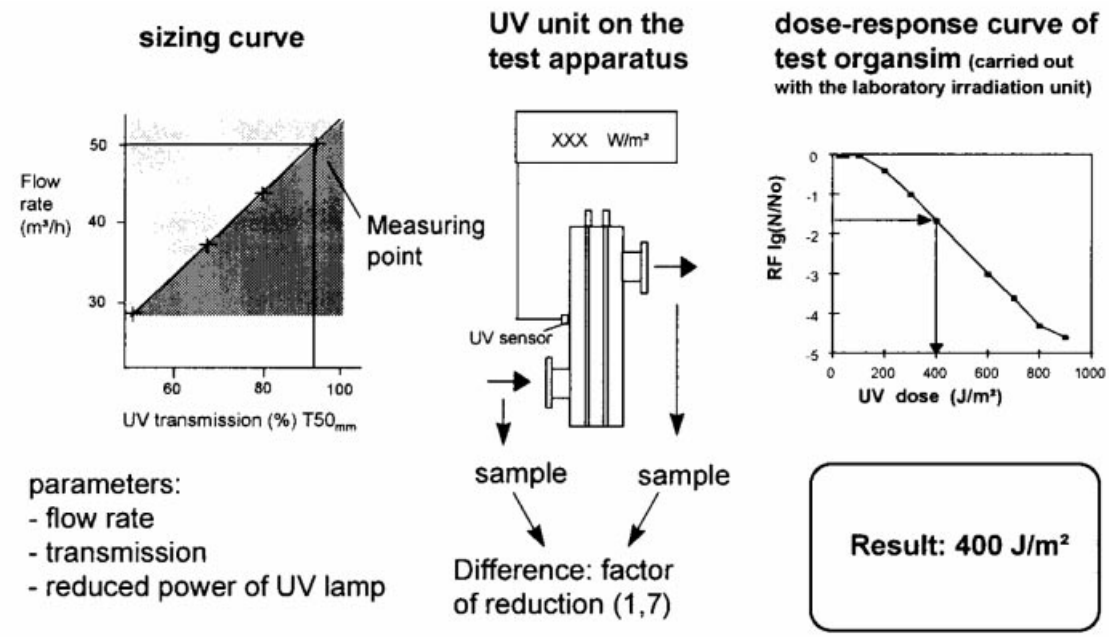

Fig. 5 Key element of Biodosimetry: Determination of the radiant exposure (J/m^2).

scale (W/m^2). This feature permits a direct comparison to be made between the sensor read out and the results of Biodosimetry. For every set of operating parameters tested, the intensity in W/m^2 can be read off and correlated with the radiant exposure in J/m^2. This permits the intensity corresponding to the hygienically required radiant exposure of 400 J/m^2 to be established. Thus, similar to the chlorine test, the method gives the operating point of the UV system. Chemical methods like the chlorine test use colourimetric determination to indirectly provide a snapshot in time of the disinfection performance of a UV system, while the method using the sensor described above indirectly provides this information continuously. The true disinfection performance of a system can only be accomplished using time consuming microbiological tests [7].

A universal threshold or alarm point for all UV systems is impossible to define because of varying distances between the quartz protection tube and the UV sensor, varying operating conditions (transmission vs. flow rate) over time in the same UV system, and different radiation intensities owing to varying numbers of UV lamps. The disinfection performance, expressed in J/m^2, or Ws/m^2, is proportional to the data display in W/m^2, but not numerically equal. Thus, different UV systems displaying different intensity values in W/m^2 will have the same disinfecting performance even if they have a common layout dictating the same sizing in J/m^2.

Displaying the radiant exposure in J/m^2 directly is theoretically possible. There are, however, problems in how well the required correction factors can be adapted to the given system and checked by the supervisory health authorities.

TEST APPARATUS COMPARISON

For the analysis of UV systems according to ÖNORM M 5873, comparative tests were performed on the test apparatus at the Austrian Federal Research and Testing Center Arsenal in Vienna (Test Apparatus A, Fig. 3; max. 450 m^3/h) and Katadyn Products Inc. (Test Apparatus K, Fig. 4; max 260 m^3/h) and their associated laboratories. The trials on Test apparatus A were performed in cooperation with the Institute of Hygiene at the University of Vienna and the Institute for Medical Physics and Biostatistics at the University of Veterinary Medicine in Vienna. The trials on Test apparatus K were supervised by Swiss Federal Institute for Environmental Science and Technology (EAWAG).

A UV system Type VR-8–350 was tested on these two stands with flow rates between 30 and 100 m^3/h and varying transmissions. In Test apparatus K the water for testing is first circulated to establish constant operating conditions before it is discharged into the reservoir after testing. Test apparatus A does not have this option and the transmission must be adjusted online. The results of the two tests showed good comparability, thus confirming the fundamental criteria regarding feasibility and reproducibility established for the introduction of the testing standard [11,12]. Equally good results were obtained for comparative determinations of the dose–response curves with the laboratory irradiation units [11,12].

Following these trials, Katadyn Products Inc. obtained official approval from the Austrian Gas and Water Industry Association (ÖVGW) that tests of Katadyn UV systems per-

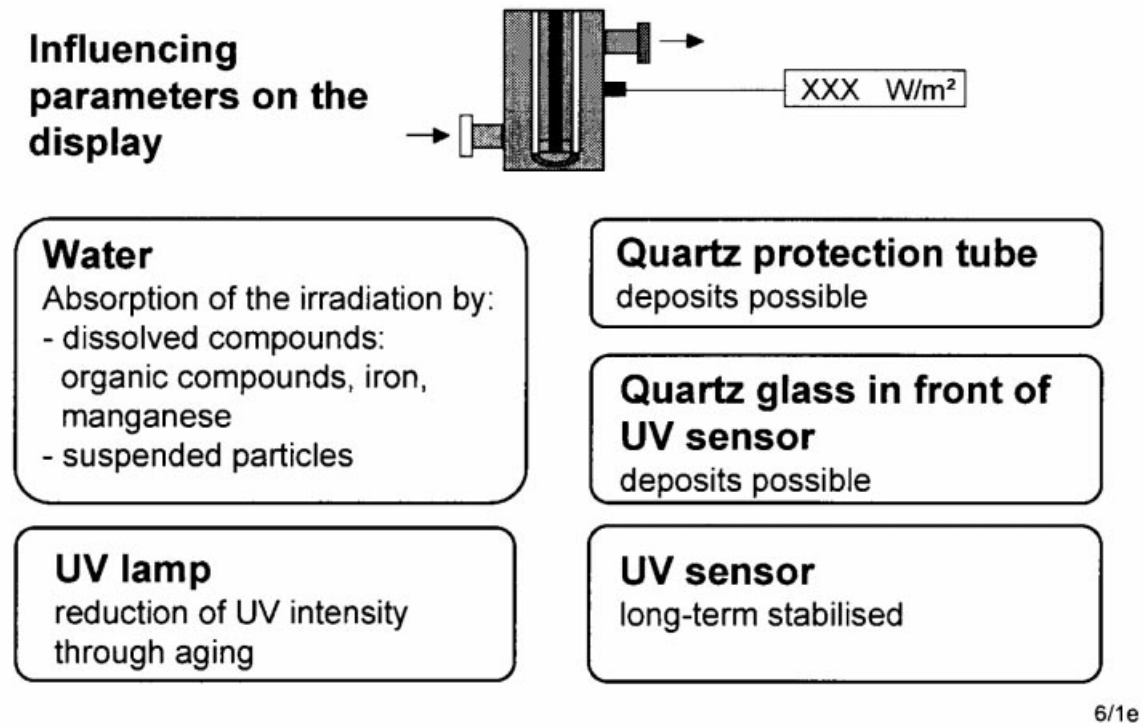

Fig. 6 Monitoring of the UV disinfection performance.

formed according to ÖNORM M 5873 on its test apparatus, accredited under the auspices of the Technical Water Test Office of the Swiss Gas and Water Industry Association (SVGW) would be accepted by the ÖVGW under EN 45001 [13].

RESULTS

The results of the biodosimetric analyses are presented. Two 400 J/m^2 sizing curves are shown in Fig. 7, one based on a mathematical model and the other on a biodosimetric determination. This graph shows clearly the difference between the calculated and the experimentally determined UV dose. The magnitude of the discrepancy varies between UV systems. Such results can be used to correct the deficiencies in the mathematical models.

Figure 8 shows the results of an extensive analysis in which for the first time different reactor geometries and UV lamps were compared. This comparative analysis was made possible by the standardised test method of Biodosimetry. All the test procedures were performed according to ÖNORM 5873. In order to be directly comparable, the three sizing curves shown all represent a 400-J/m^2 dose. Flourescein instead of sodium thiosulphate was used to reduce the transmission of the water in the tests with medium pressure UV lamps [14]. In contrast to low pressure lamps which operate at a wavelength of exactly 254 nm, medium pressure lamps possess a wide microbiologically active spectrum between 250 and 270 nm and thus require

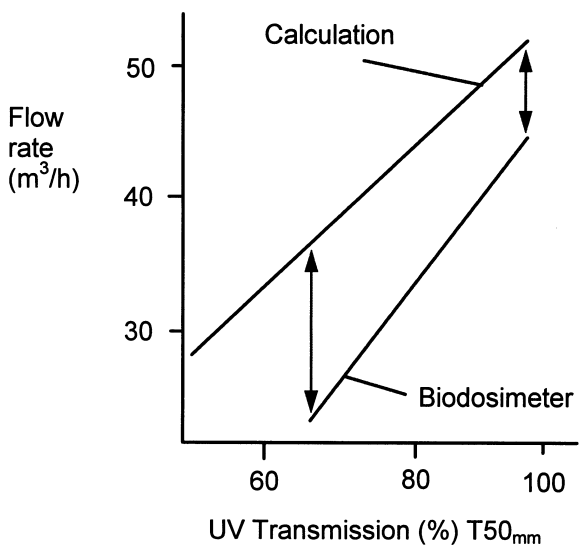

Fig. 7 Comparison of sizing curves between mathematical model and biodosimetric determination.

that the transmission of the water be decreased in this range to reflect that of naturally occurring water. The spectrum of flourescein in the range of 250–270 nm fulfills this requirement much more effectively than the spectrum of sodium thiosulphate. The Type X system is a Katadyn product and Types Y and Z are systems on the market that were tested in the process

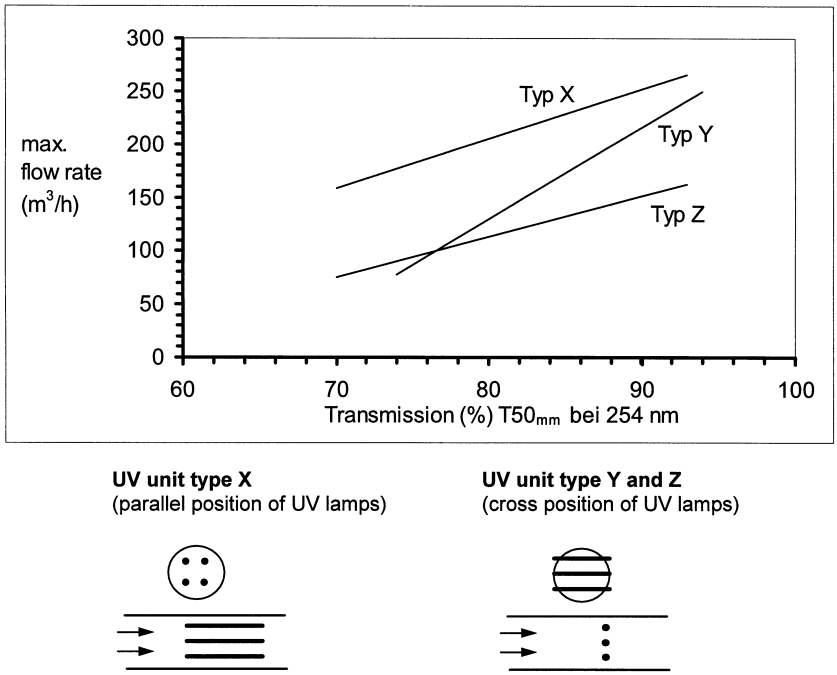

Fig. 8 Influence of the reactor design and different types of UV lamps on the microbiological performance. In order to be directly comparable, the three sizing curves shown all represent a 400 J/m^2 UV dose.

Table 1 Technical specification of the UV units in Fig. 8

Type	Nominal power (kW)	UV-C input (W)	Number of UV lamps	Average irradiation time (s) at 150 m^3/h	Length of irradiation zone (mm)
Type X	1.0	300	12 (LP)*	3.1	850
Type Y	5.1	560	2 (MP)*	0.7	≈250
Type Z	1.1	300	8 (LP)*	1.5	≈400

*LP = Low pressure lamps; MP = Medium pressure lamps.

of product development studies. The most important technical details of the UV systems are summarised in Table 1.

The disinfection performance of the UV system Type X is approximately 80–100% better than that of Type Z, even though both possess the same UV-C power, but with different irradiation times and lengths of the irradiation zone. This is surprising when considering that on the market these two systems are generally believed to have a comparable disinfection performance. The result shows that a system with UV lamps orientated at right angles to the flow must have almost double the UV-C power to achieve the same disinfection performance with the same flow rate and transmission. The Type Y system has a disinfection performance comparable to that the Type X system under good transmission conditions, even though the Type Y system has almost twice the UV-C power of the Type X, but the shortest contact time and irradiation length. With constant disinfection performance the flow rate performance of the Type Y system drops dramatically with reduced transmission in comparison with the other two systems. This shows clearly the influence of the length of the irradiation zone on the disinfection performance. For the Type X system the flow rate performance is reduced by a factor of 1.6 from 250 m^3/h (90% T50) to 160 m^3/h (70% T50). In comparison, the flow rate performance at constant disinfection performance (400 J/m$^{2)}$ drops more steeply with shorter irradiation lengths: The flow rate capacity of Type Z is reduced by a factor of 2 from 150 m^3/h (90% T50) to 75 m^3/h (70% T50) and that of Type Y by a factor of 4.4 from 220 m^3/h (90% T50) to 50 m^3/h (70% T50). The reason: with increasing irradiation zones the rate of killing is increased while the contact time remains constant.

SUMMARY

The uncertainties experienced to date by health authorities and customers alike in the evaluation of the disinfection performance can be eliminated by the use of Biodosimetry. Determining the true disinfection performance of a UV system is achieved using this standardised test procedure. The practicality and reproducibility of biodosimetric procedures have been

proven in comparative tests performed in accordance with ÖNORM 5873. Customers have been given a standardised criterion with which to objectively compare different UV systems, and with the new sensor system, health authorities have been given a tool with which to objectively check the disinfection performance of a given UV system.

ACKNOWLEDGEMENTS

I would like to thank Dr Regina Sommer of the Institute of Hygiene at the University of Vienna, Mr Alexander Cabaj of the Institute of Medical Physics and Biostatistics at the University of Veterinary Medicine Vienna, and Dr Mario Snozzi of the EAWAG for their scientific support and cooperation work.

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