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Optimal Generation of 254nm ultraviolet radiation

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Abstract: *The science of the application of 254nm UV from mercury doped glow discharge tubes has been a major topic since Johann Ritter discovered UV via its chemical inducing reactions in 1801 and Niels Finsen's 1860 work on UV therapy in treating rickets. In 1857 Siemens AG patented UV254nm creation via filamentary discharge, subsequently widely used for ozone production. By 1932 the Coblentz Congress had defined the three regions of the UV action spectrum. This paper presents the science of a new design for a sterilizer module fabricated from extruded, recycled aluminium. This novel design achieves better than D10 performance using six UV tubes per module driven by three electronic ballasts drawing a total current of only 1.26 amps at 240V single phase. This module delivers more than 45,000 microwatts per square centimetre of 254nm UV which sterilises one litre per second in a module with a dwell time of 1.6 seconds in a design with less than 0.5 bar pressure drop across each module. This system takes the electrical efficiency of 254 UV generation from less than 25% to more than 92% as measured by an NPL-traceable calibration against a current industry standard. Since 254nm UV generating tubes are also the basis of fluorescent lighting this new work on optimising the generation of 254nm UV also has application worldwide to improved efficiency of fluorescent tube electrical lighting, because we have shown that most of the fluorescent lamps operating today (particularly the T8 1" diameter) are running at less than 25% efficiency as opposed to the over 92% which is possible with the methods we describe. The work reported here shows that the Townsend equation for electron transport in glow discharge plasmas is not adequate since it does not address either plasma diameter or plasma drive frequency both of which fundamentally alter the electron energy transfer efficiencies to mercury atoms in the plasma.*
Keywords: *Ultraviolet, Glow Discharge Physics, Water Sterilisation, Fluorescent Lamps*

I. Introduction

There are many small UV water purification and sterilisation devices in use, typically operating in the 7-20 watt range. This work was not targeted at this market because these devices use very little current. The world market for UV water sterilizers runs into many billions of dollars per annum. These installations can use 1000-10,000 tubes per installation with very high electricity utility bills. The system design arising from this work was published as two Patent Applications which can be accessed on the European Patent Office website at EspacenetGlobal, http://worldwide.espacenet.com as Patent Numbers WO2007/141563 & WO2007/141562 (References 3&4). In addition there are billions of fluorescent tubes operating throughout the world using glow discharge generated UV to activate phosphor coatings on the inside of the tubes to produce visible light. The purpose of this paper is to flesh out the science of the development for teaching and research in the area of mercury doped glow discharge generation of 254nm UV and its potential worldwide applications.

The classic science of glow discharge was developed and recorded by Frank Llewellyn-Jones in his two classic monographs (References 1 & 2). A mercury doped glow discharge (typically 5-8 Torr argon gas doped with a small amount of neon to assist ignition and with a pellet of liquid mercury enclosed) is maintained by controlling the current flow through the discharge. An initial current of electrons from the cathode is accelerated in an AC field and the electrons ionize the tube gas to create ion/electron pairs. This creates an avalanche of ion/electron pairs as the created electrons accelerate down the tube. The walls of the containment must be insulating (quartz in the case of 254nm UV generating tubes and glass in the case of fluorescent lighting tubes to prevent external emission of 254nm UV) so that charges which reach the tube walls stay there, and create a stabilising field containing the plasma, thus stopping further charge reaching the tube walls. In this fashion, a plasma sheath has been created between the tube wall and the glow discharge. UV radiation, with a peak at 253.7nm, is produced from mercury 6s valence electrons being excited to the 6p state after which the electron returns to the ground state, after emitting a photon of UV radiation.

Classic beliefs include: that the mean free path for collisions of electrons and ions is much smaller than tube dimensions; ionisation in the discharge is caused by electrons, the much heavier ions making only a very small contribution; for all practical purposes, one need only look at the physics of the steady state glow discharge column, ignoring known effects over proximal approach geometry to electrodes, such as secondary emission etc. The classic physics is then the Townsend equation and its modified maths for the "abnormal glow discharge region" which is the standard operating region of a commercial glow discharge tube. This work was done by Sir John Sealy Townsend (1868-1957), the Irish physicist, probably in the 1920's, although there appears to be no definitive record. These classic equations include no terms for the dimensions of the gas discharge; that is they do not incorporate terms showing that the dimension of the plasma is crucial to the efficiency of 254nm UV creation. They also do not incorporate terms showing that the frequency of the applied AC field is crucial to the efficiency of 254nm UV creation. This new work shows that both the plasma dimension and the drive frequency are crucial, and if optimised, vast improvements in 254nm UV creation are achieved, from the current less than 25% efficiency to more than 92%. According to the accepted published wisdom before this work was done, if one wished to increase the intensity of 254nm UV emitted from a glow discharge tube, whether for water sterilization or fluorescent lighting, then the power supplied to the lamp must be increased, that is the drive current to the lamp must be increased. This new work shows that this long-held axiom is not true.

II. Optimising Glow Discharge Generation

Three separate developments were necessary to produce the optimum 254nm UV generator. In this paper all these steps are summarised here for one field tested application, that is water sterilization. The three necessary steps, in the necessary order, are:

(1) Optimisation of dimension of UV plasma & tube choice
(2) Optimisation of electronic ballast for minimum current to drive optimum tube
(3) Optimisation of sterilizer flow and construction design to optimise bug kill at minimum cost

The investigation of the effect of gas discharge plasma dimension on emission efficiency at 254nm was achieved experimentally by buying a range of 254nm UV emitting tubes of different diameter. The possible selection of tubes for test is limited because not many different tube diameters are manufactured today. All the test tubes were driven from a common ballast design in this experiment to avoid any errors due to circuit efficiency. The measurements of the integrated 254nm peak counts were made at a distance of 6 metres from the tubes, in a darkroom, to ensure point geometry, that is to ensure that effects of tube dimension were negligible. This work was done at Loughborough University by Dr John Harry, Electrical Engineering Department. The equipment used in the measurements was all secondary standard NPL traceable, owned by the University. The tubes evaluated in this work were all low pressure (around 7 Torr) glow discharge tubes. The relevant set of results is shown as Figure 1. It is obvious that plasma dimension is a very strong factor in 254nm UV emission and that there is an optimum at 15mm diameter. Given this result, the rest of the design of the optimum 254nm UV sterilizer reported here was based on using the 15mm internal diameter GHO365L mercury discharge tubes bought from LightTech Lamp Technology Ltd, Hungary, www.lighttech.hu

The investigation of the effect of plasma drive frequency on emission efficiency at 254nm was effected experimentally by building an electronic ballast circuit based on International Rectifiers USA IR2156 chips but with a power supply capable of being driven over a frequency range 15-70 kHz. Figure 2 shows that drive frequency is a very strong factor in 254nm UV emission from glow discharge tubes and that there is a very clear optimum efficiency of operation at 55-57.5 kHz. Current glow discharge tubes used in UV sterilizers and fluorescent lamps operate at around 20kHz. This is well below the now-known optimum frequency of 55-57.5kHz reported in this paper, which would minimise operating costs if adopted. Various other optimisation steps had to be taken to design/manufacture and test the optimum ballast circuit recorded in Figure 3, the details of which have already been published in full detail as WO2007/141562. The experimental effort to measure the UV output at different tube frequencies whilst keeping the tube emitting is not trivial. We found that any variation in frequency is liable to cause the tube to shut down and to be difficult to re-ignite. For the 15mm diameter GHO36T5L tubes used, in order to ensure the tubes remained lit and stable, and were ignited every time, the igniter circuit had to provide 450V at 58.63kHz following a pre-heat at 140V at 0.9A and 75.94kHz for one second only. To achieve the over 92% efficiency reported here, it is **essential** that the tube drive voltage is kept over 170V at all times whilst the tube is ignited. Many commercial ballasts use no pre-heat circuits to condition the tubes, and as a consequence have to use much higher ignition voltages, typically up to 2kV, with a resultant slowdown in time to achieve tube output stability, and reduction in lamp lifetime. The ballast circuits as reported here were built by Bob Goodman of Xcel Systems Ltd, Luton, UK.

Having optimised the choice of tube diameter, and the selection of the optimum operating drive frequency for the glow discharge tube, the next step was to benchmark the total UV output integrated under the 253.7nm peak from our new system by comparing it with a current industry standard, a T8 commercial germicidal tube fitted with its own ballast from one of the world's leading suppliers. The comparison measurement was done at a secondary-standard NPL certified independent facility, operated by Dr Harry

Moseley and located at the Photobiology Unit, University of Dundee, using systems based on Bentham spectrometers kept in NPL calibration.

The graphed results were all based on an average of 10-30 tubes of each type being tested.

The combination of the optimised drive frequency, the optimum tube diameter, and our optimised ballast resulted in overall 92% wall plug efficiency compared to 25% for a commercial 25mm diameter tube using the manufacturer's supplied ballasts.

It should be noted that the study of glow discharge tubes was a hot topic in the period 1947-1970 and this effort led to all the current glow discharge-based fluorescent lamps. Very little work has been done in the last fifty years on looking at the basic wall plug efficiency of glow discharge lamps and we know of no other work which has shown the very strong dependence of UV output in glow discharge on tube dimensions and drive frequency. The international effort on gas discharges after 1970 first moved on to arc discharges, which now illuminate all our streets, airports, and supertankers in the form of the yellow sodium and blue mercury discharges. These of course are the largest commercial markets. Following the arc discharge research surge, the world's physicists moved on to gas lasers, which, following Theodore Maiman's seminal work on the ruby laser, became the dominant research topic leading to many applications from space warfare to medical therapies.

The UV efficiency gains were field tested by construction and deployment of novel prototype sterilizer modules, designed for mechanical and flow efficiency. Their performance in terms of bug kill rate, was then analysed. To ensure such units can be manufactured as cheaply as possible, we based the mechanical design on recycled aluminium and a single 1 metre long, 1 metre wide, extrusion. Figure 4 shows a single sterilizer module. The plastic water sealing gaskets are shown in red. The UV tubes (eight are shown in this unit, but six tubes per module is the optimum) are each fitted within quartz sleeves so that the water to be purified is not in contact with the UV tubes because they contain minute quantities of mercury, and to allow UV tubes to be replaced when necessary without taking apart the system. The UV tubes are fitted into holes in the extrusion using further gaskets. The internal diameter of the top/bottom water inlets/outlets is 100mm. Figure 5 shows how a complete UV system for major-scale water purification plants can be built up from these modules by plugging them into an aluminium manifold of inner diameter 154mm. To achieve the best performance we have established that the separation of each module has to be 400mm, and the minimum water pressure at the last installed module has to be greater than 1.5 bar. The mechanical and fluid system design calculations for this new optimised water sterilizer were done at TUV NEL East Kilbride using commercial software packages, namely ANSYS Fluent CFD from www.ansys.co.uk and Adept Scientific MathCas/VisSim from www.adeptscience .co.uk

A complete single six-tube prototype unit, one metre wide, in extruded aluminium, to the design shown here, was built and tested outdoors at the Scottish Water purification plant at Luss on Loch Lomond and run for 24 hours continuously. Samples were taken every hour. Samples were fully analysed at an independent laboratory for all the micro-organisms present. Since our system has a design bug-kill dose rate way beyond that needed to achieve D10 status, which is defined as the UV dose to cause a 90% reduction In CFU's (coliform forming units), the result that we had secured a 100% complete sterilisation in a single pass was as expected.

III. Conclusion

We have shown that it is possible to achieve over 92% wall plug efficiency in generating ultraviolet from commercially available tubes by optimising the tube diameters, drive frequencies and ballast designs. Prior to our work the standard electrical efficiency figure quoted in textbooks and papers was 25%. This is still the case!! One of the main objectives in publishing this work is to attract the attention of theoreticians and mathematicians to the fact that the Townsend equation does not provide an adequate model of electron transport in glow discharge plasmas because it contains no terms for plasma dimension or drive frequency. We have shown that both of these factors have very substantial effects on electron capture rates at mercury sites and hence on the generation of 254nm UV, which drives the coating phosphors inside fluorescent lamps, and kills the bugs in water/air sterilizers.

Having proved out the science of the new glow discharge geometry and optimum drive frequency we tested the robustness of our results by building and testing a full scale one meter wide extruded aluminium test bed water sterilizer. This was operated outdoors in a hostile environment. As reported the results of this test confirmed the lab results of over 92% UV generation efficiency.

Examples of the potential commercial areas of application for these new advances in glow discharge UV are: water sterilization (including small sized solar powered units for the Third World); improved efficiency fluorescent lighting tubes; cost-effective sterilized air in aircraft, submarines, and similar enclosed environments, because of reduced electrical current requirements.

References

[1]. F. Llewellyn-Jones, *The Glow Discharge*, (Methuen, London: Wiley, 1966)
[2]. F. Llewellyn-Jones, *Ionisation & Breakdown in Gases*, (Methuen, London:Wiley,1966)
[3]. Patent WO2007/141562, December 2007
[4]. Patent WO2007/141563, December 2007

Figure 1: Optimum 254nm Emitter Diameter

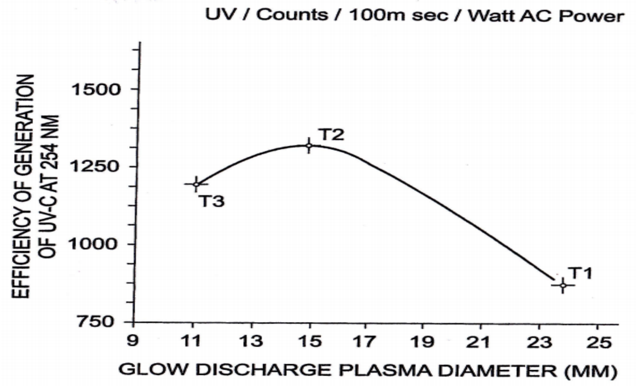


Figure 2: Optimum Ballast Frequency for 254nm emission

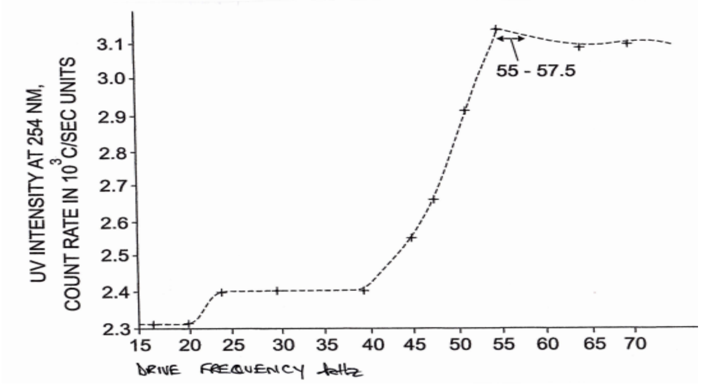


Figure 3: Optimum Ballast Design for 254nm tube operation

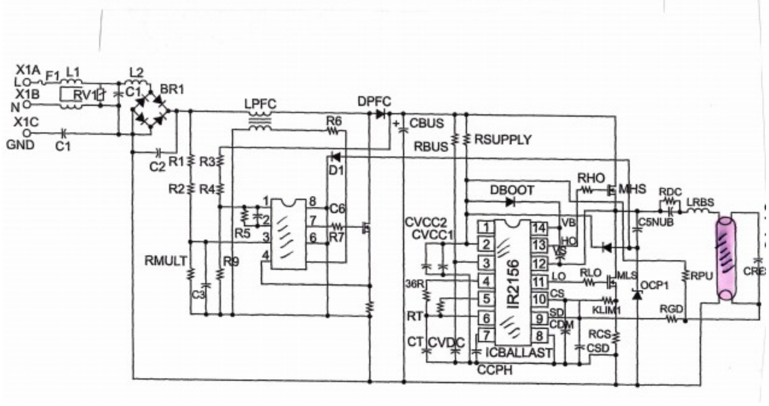


Figure 4: Optimum UV Sterilizer Module, 100cm long

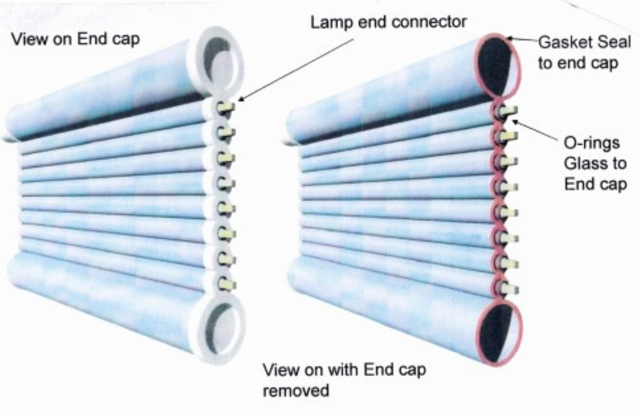
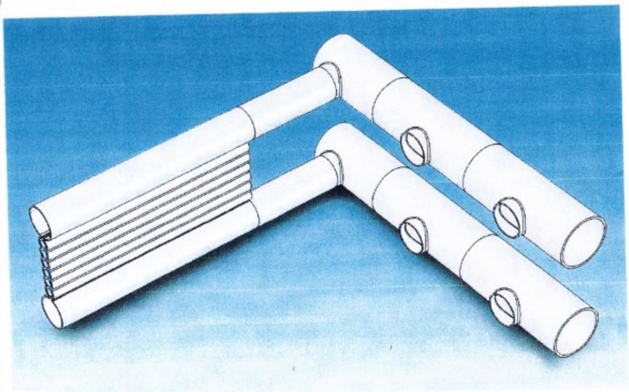


Figure 5: Multiple Module Stacking Design



Manifold arrangement with UV Steriliser No. 0 fitted. It is assumed that water enters through the top manifold and leaves by the bottom manifold