# Biofilm prevention in the generator of a direct drive wave energy converter

C. Li, S. Turkman, N. J. Baker, J. Finlay, E. Ryan

*Abstract*—**As wave energy approaches commercial reality, long term biofouling prevention within electrical generators operating in the marine environment must be considered. This paper gives a comprehensive discussion of biofilm build up and describes early-stage work to investigate the use of UVC irradiation to control biofouling within the electrical machine and bearing surface of a wave energy converter. Initial investigations were conducted by using flat panels (600mm x 220mm) to simulate the active gap of an electric generator. Diatom dominated biofilms were produced using an artificial slime farm which allows test panels to be subjected to a continuous dynamic flow. The light source of UVC irradiation was provided by Light Emitting Diodes with 278nm wavelength. The effectiveness of the biofilm prevention by UVC has been evaluated by Image Analysis. The results confirm that using UVC can achieve a significant control over the development of biofilms. It has also been demonstrated that intermittent UV can achieve successful biofilm prevention on submerged surfaces, saving energy and prolonging battery life in early-stage demonstrations. However, observations indicate the actual UVC light intensity may perform below the manufacturer's specifications, and this could lead to a detrimental effect on its biofilm control performance.**

*Keywords*—*Antifouling, Biofilm, Slime Farm, Ultraviolet, Wave Energy Converter*

## I. INTRODUCTION

POWER take off in a wave energy converters has a number of unique requirements. It must convert low speed oscillating motion into electricity in a reliable, low maintenance manner. A direct drive system, where the electrical machine is optimised to operate at low speed, has the potential to offer a mechanically robust and simple solution. Similar to a hydraulic power take off, the only regular maintenance would be to inspect and replace the seal between moving parts. One strategy for removing regular maintenance is to have an unsealed system, i.e. one where sea water is allowed throughout the electrical machine. A fully flooded electrical machine has benefits in terms of cooling, but poses challenges relating to reliability, corrosion, biofouling and lubrication [1].

Electrical machines operate by the interaction of two parts moving relative to each other in the presence of magnetic forces. A lubrication system is required to resist attractive magnetic forces and preserve a physical gap between the two components. In a rotational electric machine, the two components are called a rotor and stator, and the lubrication system is usually a set of ball bearings recirculating around the rotor shaft. In a linear machine, the components are called the stator and the translator, and the lubrication can be a set of rollers, or a solid contact surface. In ship propulsion, lubrication is often by polymeric bearings. It has been shown that polymeric bearings may be suitable for the power take off generator in wave energy converters[1] [2].

In a generator, the distance between the active part of the stator and rotor (or stator and translator in the case of a linear machine) is referred to as the magnetic gap. The size of the magnetic gap has a huge influence on the electric machine – with a smaller gap usually giving



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improved performance. Any sleaving or encapsulating of the rotor is included in the magnetic gap, so the physical distance between the stator and translator is often smaller. This is referred to as the 'air gap' and is usually limited by achievable manufacturing tolerances. For example in a small high speed machine we might expect a magnetic gap of 1mm, consisting of a 0.5mm retaining sleeve and 0.5mm physical gap. In slower larger machines, the sleeve may not be required, but tolerances would require an airgap of 1.5mm or more.

In wave energy, machines are likely to be large and slow. It is likely the magnetic gap will need to include some encapsulation to prevent water ingress. In prototype linear generators for wave energy, we have assumed a physical airgap of 1mm. If the machine is to be run flooded, there will be sea water in the air gap. The air gap may also act as a lubrication surface in the case of solid contact sliding bearings. Successful operation of the generator therefore relies on preventing biofouling in this 1mm gap.

Fig. 1 Prototype of an IPS buoy wave energy converter being developed. The yellow parts oscillate, the red part is the translator of an electric generator, which is coupled to the water contained in the cylinder.

Fig. 1 shows a prototype generator that is being developed which will be installed in the North Sea, consisting of a submerged linear tubular electrical machine [3]. A magnetic tubular translator will oscillate within a cylinder that houses stator coils. Lubrication will be by way of solid polymer bearings. In order that the active part of the electrical machine can oscillate smoothly, it is imperative that biofilm is prevented from colonising on the bearing surface, which also makes up the magnetic gap of the electrical machine. This prototype will be used to demonstrate biofilm prevention in generators developed for direct drive power take off in wave energy converters.

The system will have a slow reciprocating oscillation, with a peak speed of perhaps 1m/s. For most wave energy converters there will be brief static periods twice in every wave, and in calm seas these could be prolonged to several hours or even days. In low energy sea states oscillation amplitude could be less than the fully rated amplitude, meaning different parts of the bearing surface could be exposed for different amounts of time.

This paper systematically discusses the testing procedure and impact of UVC irradiation on biofilm prevention within the active part of an electric generator in a prototype wave energy converter, with a view to accelerate its translation to full-scale applications.

## II. Biofilm Formation

### *A. Formation*

In aquatic systems microorganisms exist predominantly as surface-attached communities called biofilms [4]. Biofilm on ship hulls is frequently dominated by bacteria and algae. Bacteria attach to surfaces immersed in the sea very rapidly (minutes) and usually attached by mucilaginous fibrils [5]. Diatoms also attach rapidly, but the presence of bacteria is not essential for their adhesion and subsequent colonisation [6]. In natural environments, algal biofilms are often dominated by diatoms, but other algae such as cyanobacteria (blue-green algae) and filamentous green algae are also frequently present [7]. The successful colonisation of the algae propagules (e.g. individual cells, vegetative fragments or spores) on a substrate surface, particularly in turbulent flow conditions, is achieved by having a strong adhering ability through secretion of adhesive polymers referred to as extracellular polymeric substances (EPS) [8]. Growth of biofilm on a surface can be determined by various factors, such as the abundance and type of species, the availability of nutrients, temperature, light, the submerged surface condition and hydrodynamic characteristics [7, 9-14]. Both diatoms and bacteria can chemically alter the environment close to the surface on which they reside [8, 15]. Over time, as the biofilm develops, more complex organisms, such as barnacles, mussels, and other macroinvertebrates, begin to settle and grow on the surface. This creates a diverse community of organisms known as a macrofouling community. (Fig. 2).

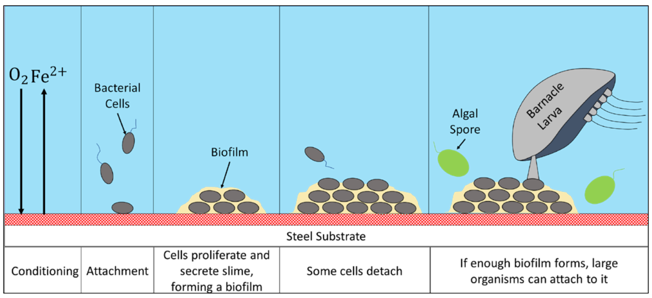



Fig. 2 Illustration representing the stages of biofouling formation (adapted from [17])

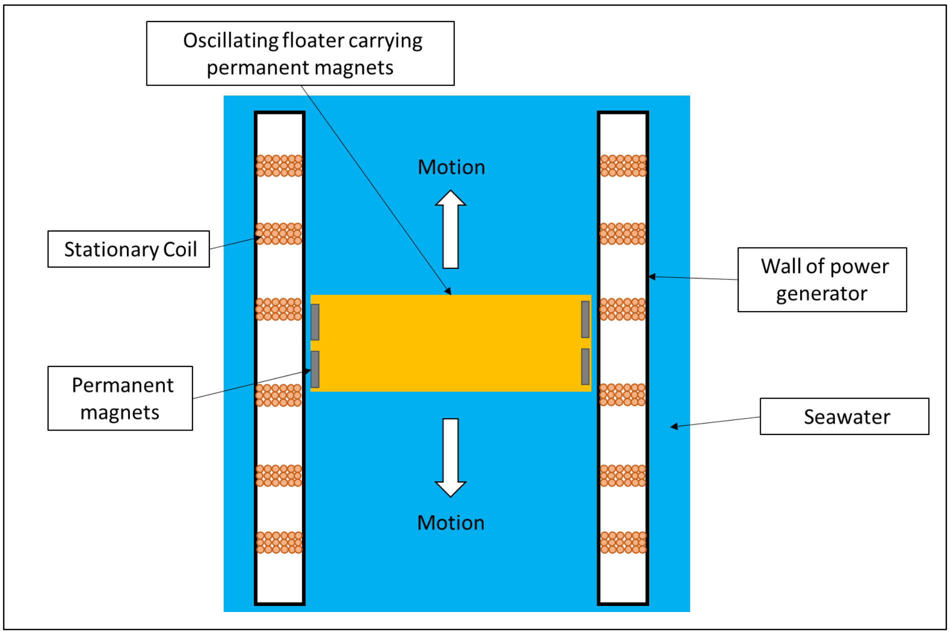



Fig. 3 Sketch of the oscillating power machine

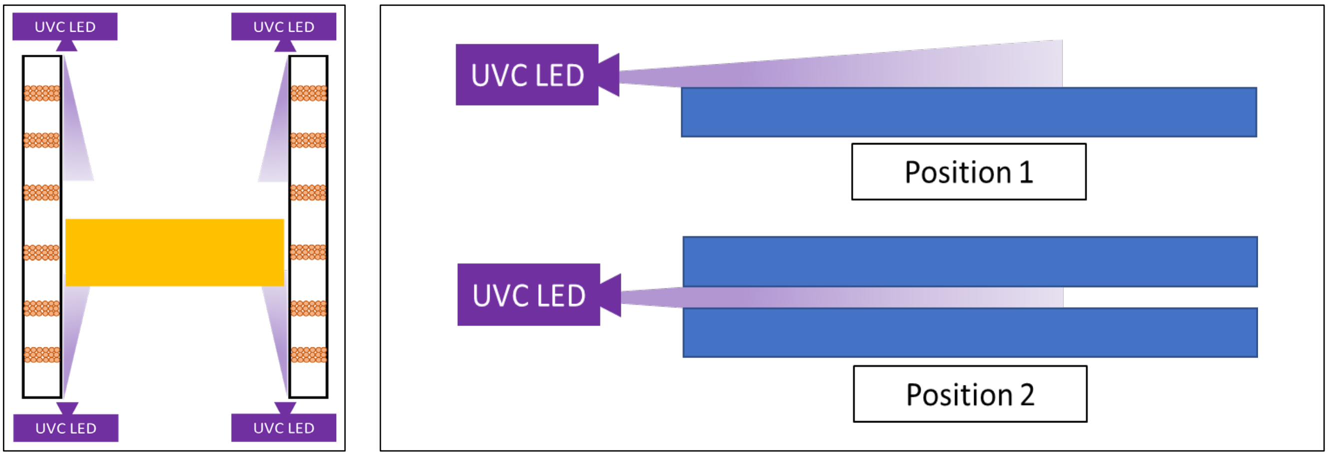
*B. Suppression*

In a marine environment, biofilm can be formed within hours, from the moment that marine structures are immersed in seawater [17]. Due to the presence of biofouling, corrosion of metals can be promoted and accelerated. Microfouling induced corrosion (MIC) occurs as a product of biofilm formation and can be described as the local modification of the chemical environment through microbiological processes [18]. For example, bacterial corrosion occurs wherever non-sterile water is in contact with a metallic surface. Furthermore, macrofouling communities, which consist of various organisms attached to submerged surfaces, can create localized microenvironments with reduced oxygen levels. These anoxic conditions provide a favourable environment for the growth of anaerobic bacteria, including sulfate-reducing bacteria (SRB) [19]. SRB are commonly associated with MIC and play a significant role in the corrosion of metals. They can utilize sulfate as an electron acceptor in the absence of oxygen, leading to the production of hydrogen sulfide ($H_2S$) as a metabolic byproduct. $H_2S$ is highly corrosive and can react with metal surfaces, promoting the corrosion process [20, 21]. Biofilms can block or reduce thermal efficiency in pipeline systems as the internal diameter may be reduced with biofilm development, thereby restricting the fluid flow through the pipe [22, 23].

Fig. 3 shows the present work consisting of a permanent magnet translator oscillating in an unsealed system flooded with sea water. Thus, a fully flooded electrical machine is exposed to biofouling protection challenges. Biofilm settlement will interfere with the operation of this generator. Macroalgae have the potential to colonize and occupy the air gap and bearing surfaces of the electrical machine. The microbial accumulations can potentially increase surface frictional forces which in turn impede their ability to efficiently produce power [24]. The weight of fouling also leads to increased drag and reduced buoyancy [25]. There is no quantitative data for biofilm impact on Wave Energy Converters (WECs). However there have been some aquaculture studies carried out where the weight of biofouling on a net has been recorded at 7.8 kg $m^{-2}$ after only 21 days of immersion. Furthermore, weight increases of up to 200-fold have been recorded on aquaculture nets [26]. Mechanical removal of these marine growths could result in the protective paints being stripped off and lead to an exacerbation of surface damage. A consequence of fouling settlements is an increased demand for cleaning operations, either because of additional underwater surface cleaning or even for coating replacement or costly structure repairing. If the settling of initial microorganisms can be prevented, fouling may be greatly decreased or eliminated [9].

Copper and copper/zinc compounds are commonly used as biocides against biofouling on surfaces exposed to seawater. These antifouling (AF) paints require periodic application, enforcing regular maintenance. This is challenging, especially in offshore WECs with complex moorings. WECs will need to be removed from the marine environment every 3–5 years, according to the AF manufacturer specification. This will raise costs of paint removal and repairing, in addition to health and safety concerns for maintenance personnel [27]. Furthermore, current AF paints can have a negative impact on their environment, which should also be considered, see [28] for example.

Apart from paints, within antifouling research, a number of innovative antifouling strategies have also been introduced either in their infancy or had so far limited success. One of those is through the projection of Ultraviolet (UV) radiation which is a promising option that has been well established in other fields, such as the disinfection of medical devices, drinking water and wastewater treatment [29, 30]. Ultraviolet light is that portion of the electromagnetic spectrum that lies between

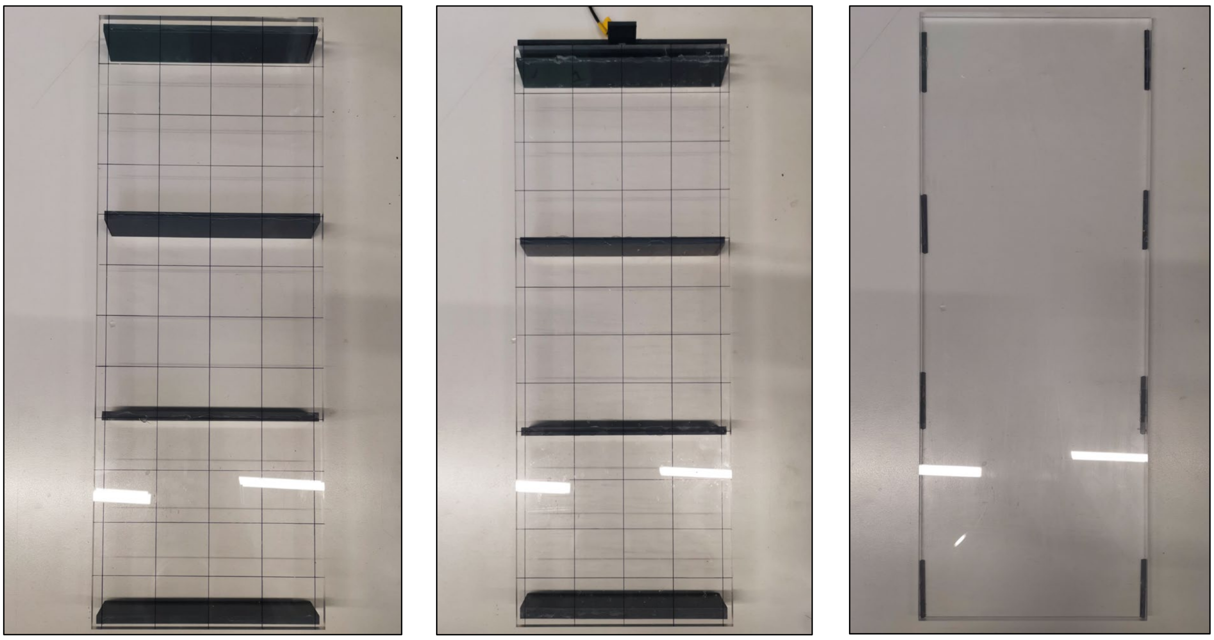



(a) (b)

Fig. 5 Sketch of the UVC projection onto test surfaces (a) The initial design concept with UVC projection towards to niche area surfaces (b) panel arrangements

X-rays and visible light. The biological effects of UV radiation vary enormously with wavelength, the UV spectrum is further subdivided into three regions: UVA (315 and 400 nm), UVB (280 and 315 nm), and UVC (100 and 200 nm). Practical application of UV disinfection in certain environments to kill microorganisms relies on UVC [31-33]. The high energy wavelengths UVC band typically fails to reach the earth's surface because of filtering by ozone in the upper atmosphere [34]. Thus, creatures are likely to have evolved longer UV wavelength (UVA and UVB) resistance rather than to UVC [35]. If the UVC light is absorbed by the DNA and RNA of microorganisms at a sufficiently high volume, then the bacteria and algae of the early attachment stages described in the succession model are inactivated and no longer able to replicate [16, 36]. It would therefore prevent the biofilm from developing at the initial stage. Further appeals of UV radiation as AF is that it is able to cover irregular shapes with different surface characteristics [37], without resulting in accumulation of toxic by-products in the ecosystem [38]. The efficiency of UVC fouling prevention is related to the projection distance of the light source, the operating duration, and the microorganism species in the marine environment [39-41].

The effect of UVC antifouling methods on biofilm has been widely demonstrated by various investigators [42-45]. However, there is a lack of information on UVC protection being applied to WECs, particularly at the biofilm forming stage. There is also a scarcity of information on the effectiveness of UVC on a submerged slowly reciprocating object. Hence, in the present study, an attempt has been made to evaluate the efficacy of UVC treatment, as an alternative AF solution, to control biofilm formation in the active part of a fully flooded electrical machine and its bearing surfaces. The main objective of this investigation was to conduct experimental observations to explore the effectiveness of preventing



(a) (b) (c)

Fig. 4 Testing panels: (a) control surface (b) base surface with UVC LED installed beside (c) top surface with 1mm thickness gaskets attached biofilm settlement on submerged surfaces using intermittent UVC irradiation.

## III. Materials and Methods

### A. Surface Preparation

According to Fig. 4, the most vulnerable and difficult places to provide antifouling solutions are the surfaces within the magnetic gap (1mm) between the linear tubular machine and the oscillating floater. Restricted by this specification, it is not possible to precisely control AF paint coating thickness or to use metallic materials without disturbing reciprocating oscillation motion or weaken the magnetic field strength. Fig. 4 (a) indicates the UVC has been thus introduced into this niche area of the electrical machine to achieve fouling free operation.

Several flat panels (600mm x 220mm) were used to simulate the original surfaces between the moving parts. Each testing panel had 50mm × 50mm reference grids which can be used to measure the coverage of fouling. As shown in Fig. 4, the flat panels were separately arranged into two positions replicating the oscillating motion. Position-1: there is no 1mm magnetic gap formed on top of tubular machine inner surface; Position-2: there is a 1mm magnetic gap formed from the section where the oscillating floater is within the linear tubular machine inner surface; Fig. 5 (b) shows the panel used as foundation surface with UVC LED installed at central of side edge. For Position-2, Fig. 5 (c) shows a separate panel used as the top surface with 1mm thick gaskets along edges. The UVC LED was installed beside the panel's edge to investigate the effective UV protection distance.

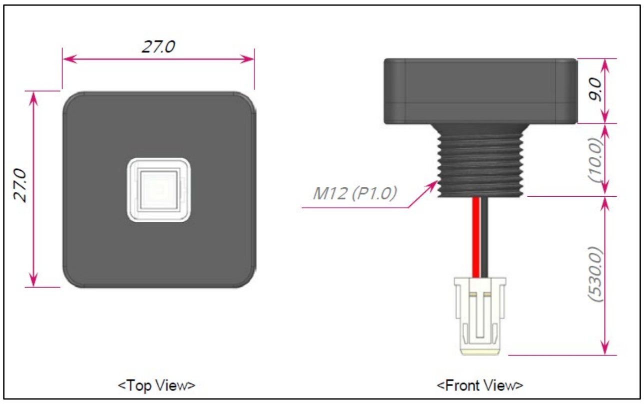



Fig. 6 Waterproof UVC LED module

### B. UVC LED and Setup

The UVC irradiation source used in the present study was a UVC Waterproof Module (Fig. 6) with a peak wavelength of 278 nm and exterior dimensions of 27mm × 27mm × 9mm. Under the design operation, the irradiance range is within 340 – 930μW/cm².

In order to avoid component damage and ensure the LEDs operate at the maximum UV output, the power source voltage was gradually increased until a desired voltage of 12V was achieved according to the manufacture's specifications. Shown in Fig. 7, the subsequent tests were therefore conducted with LEDs supplied by a DC digital power supply set to a constant 12V DC, 0.023A. To confirm operational irradiation intensity, each UVC LED output level was measured using an EXTECH SDL470 UV-C wavelength meter in direct contact with the sensor face to record the maximum intensity output.

To design and source components for antifouling purposes, it is essential to estimate the required UV intensity. A dose of 10 – 300J/m² irradiation has been found to kill 99.9% of planktonic bacteria [46-48]. Elsewhere, a UVC intensity antifouling threshold of 0.03μW/cm² has been found [43]. However, a higher intensity threshold would always be necessary when considering the distance from the UV source to the target surface, the water quality and the potential microorganism species. It is suggested that the minimum required UVC intensity to inactivate 90% of algae is more less than 1.16μW/cm² [45] according to a rate constant (k = 0.0023m²/J) which is taken for a species of algae obtained from existing data [40]. Table 1 shows the results of the light irradiance intensity measurements – somewhat lower than claimed by the manufacturer.

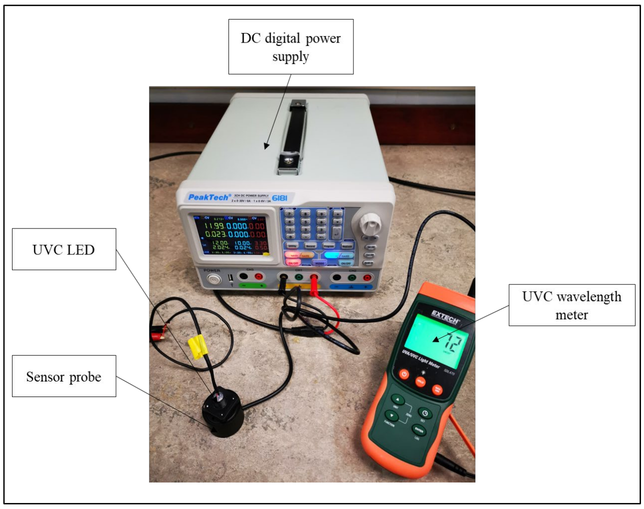



Fig. 7 LED irradiation measurements

Table 1

LED UVC Irradiance measurements

| LED Module | Minimum | Maximum |
|---|---|---|
| *LED 1* | 103μW/cm² | 113μW/cm² |
| *LED 2* | 160μW/cm² | 195μW/cm² |

Some studies found that the periodic application of UVC can also inhibit the accumulation of biofouling. In [47] mature biofilm was suppressed with an approximately 99% killing rate in a relative long treatment time (~60mins). During a nine-month in situ trial, UVC illumination at a duty cycle of 1:2 (10mins on, 10mins off) was successfully used to inhibit biofouling [41]. The success of the intermittent application of UVC raises the possibility of refining illumination periods to determine an optimal illumination pattern that maximizes AF effects while minimizing power consumption [41, 49, 50]. In the present study, a programmable timer was introduced to evaluate the impact of intermittent application of UVC to achieve a desired antifouling performance. The timer was initially programmed with a duty cycle of 60mins on, 60mins off.

### C. *Cultivating biofilm*

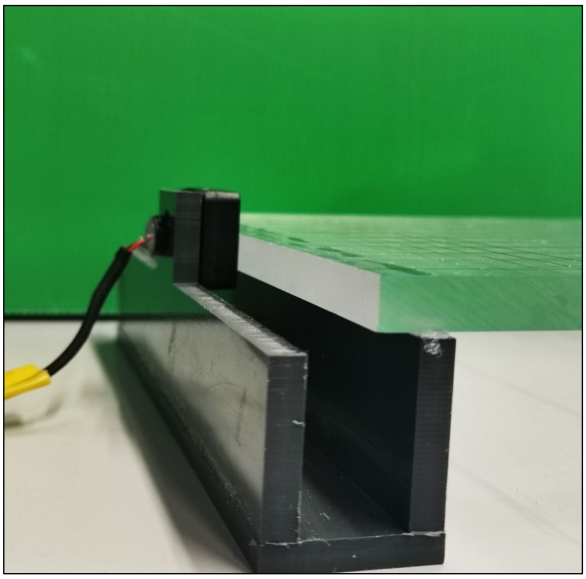
Tests are carried out for the open surface (Position-1) and the 1mm gap (Position-2). Two operational scenarios have been considered: functional and malfunctional conditions. The functional condition refers to the UVC antifouling sensors operating from the beginning of the trials, i.e, from the time of submersion. The malfunctional condition refers to UVC antifouling sensors partly or fully encountering issues, therefore being un-powered for a period. Accordingly, the biofilm cultivation and tests will be separately based on these two conditions.

Fig. 8 Slime farm with showing flow circulating direction

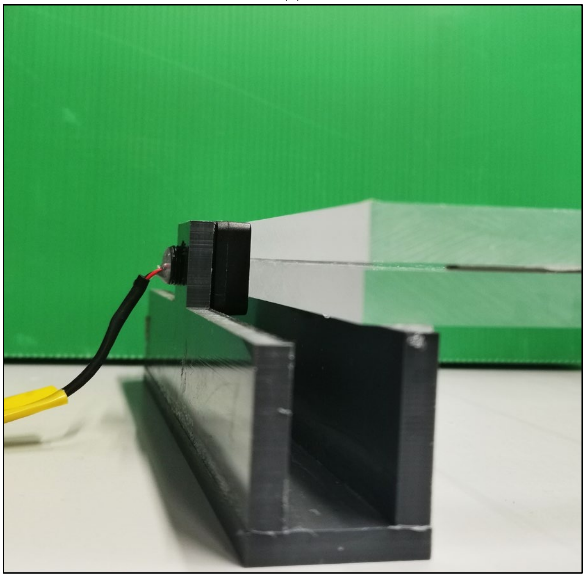
To achieve biofilm growth, an artificial slime farm was designed and manufactured to simulate the natural conditions required for biofilm growth and allows test panels to be subjected to a continuous dynamic flow. The slime farm (see Fig. 8) was built with six interconnecting rectangular water tanks (990mm × 400mm ×180 mm). Testing panels (Fig. 9) were placed at the bottom of the tank, promoting biofilm settlement and growth. A Xylem Flojet magnetic coupling centrifugal water pump was used to give a continuous flow around the series connected tanks. The rig contained 150 L of constantly circulating artificial seawater (33-35 %) mixed with Guillard's (F/2) Marine Water Enrichment Solution. The water temperature was kept between 20 °C and 22 °C using fish tank heaters. To simulate daylight and to encouraging fouling by algae as well as bacteria, six 24-hour aquarium lighting tubes were fixed above the tank.

The inoculum of microbes was collected directly from the research vessel, Princess Royal, owned by Newcastle University. The research vessel is berthed and operated around the port of Blyth, on the Northeast coast of England where the sea temperature changes between 6.7° and 15.3°C throughout the seasons.

When under the functional condition, the duration of growing biofilm on the test surfaces used was 21 days (7 days of water environment set-up and starter cultures running, 14 days cultivation). For the malfunctional test, the duration of growing biofilm on the test surfaces was 35 days (7 days of water environment set-up and starter cultures running, 14 days cultivation without projection UVC, and 14 days with UVC).



(a)



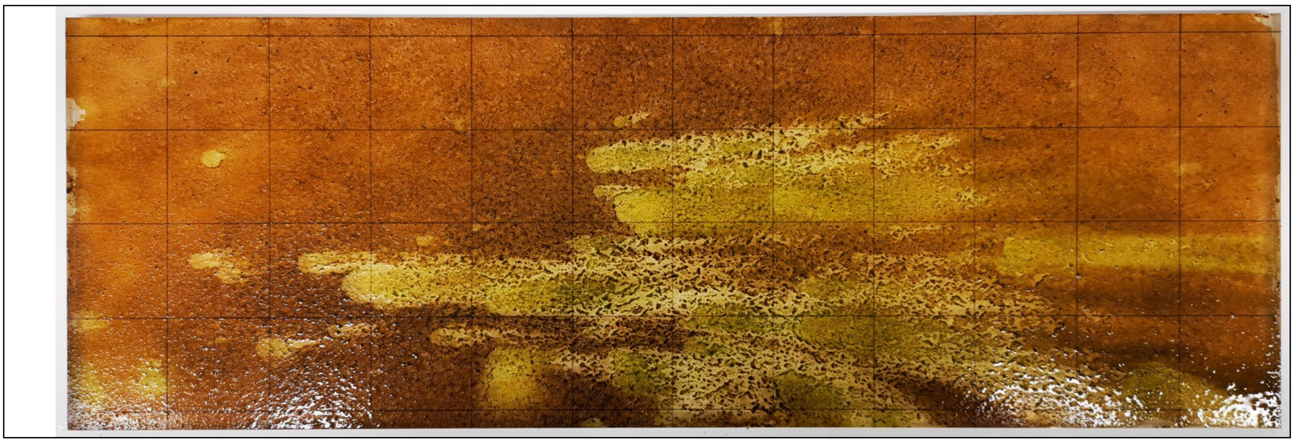
(b)

Fig. 9 Completed arrangement of UVC LED with testing panels (a) Responding surfaces arrangement at position-1, (b) Responding surfaces arrangement at position-2

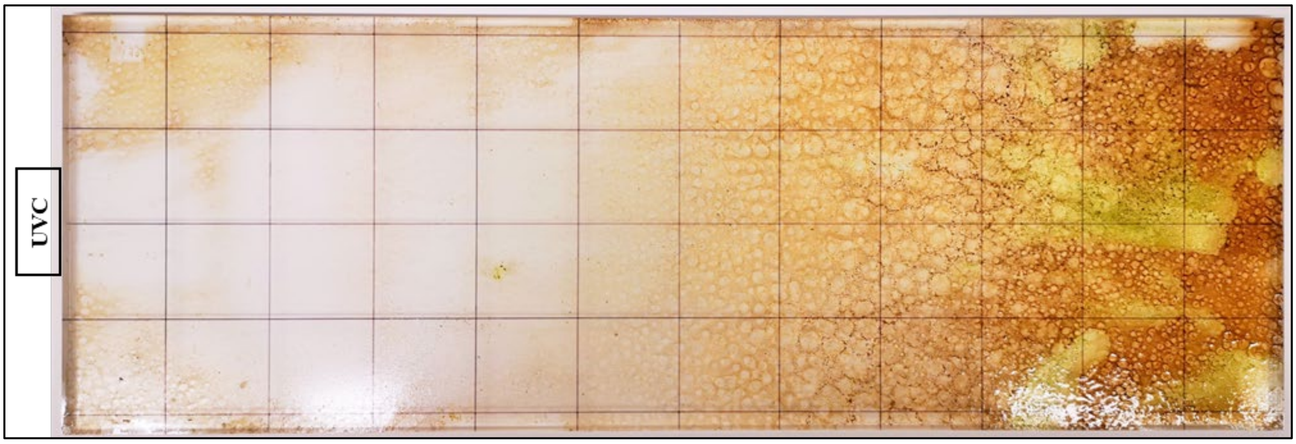
## IV. RESULTS AND FINDINGS

### A. *Investigation of antifouling effectiveness under UVC LED functional condition*

By day-14, the control surface had 100% biofilm coverage (Fig. 10 (a)). With the UVC dosage controlled to an operational cycle of 60mins on, 60mins off, Fig. 10 (b) shows a fully effective antifouling distance of 280mm, plus a further distance of 180mm where antifouling is still moderately effective within the 1mm gap. The UVC test results in a 550mm² completely biofilm free area, accounting for 41% of the total surface area. Approximately 500mm² (38% of total) area had a thin biofilm, where mildly effective antifouling can still be



(a)




(b)

Fig. 7 Biofilm distribution over testing surface (a) control surface (b) from arrangement of Position-2 with 1mm gap

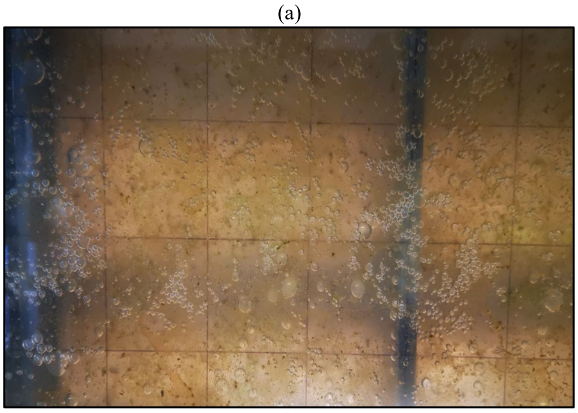
clearly recognised. The UVC light was projected from a flat LED light probe and angles between 30° – 35° from its central axis can be seen to give efficient biofilm protection.

Unfortunately, the UVC LED used for Position-1 failed within a week of testing due to water ingress, so at this stage we are unable to compare the UV protection of the flat surface (Position-1) with the 1mm gap case (Position-2). It is clearly critical to confirm manufacturer's claims of waterproofing and salt resistance prior to deployment in the marine environment. Further tests about malfunctional condition have been discussed in the following section.

### B. *Investigation of antifouling effectiveness under UVC LED malfunctional condition*

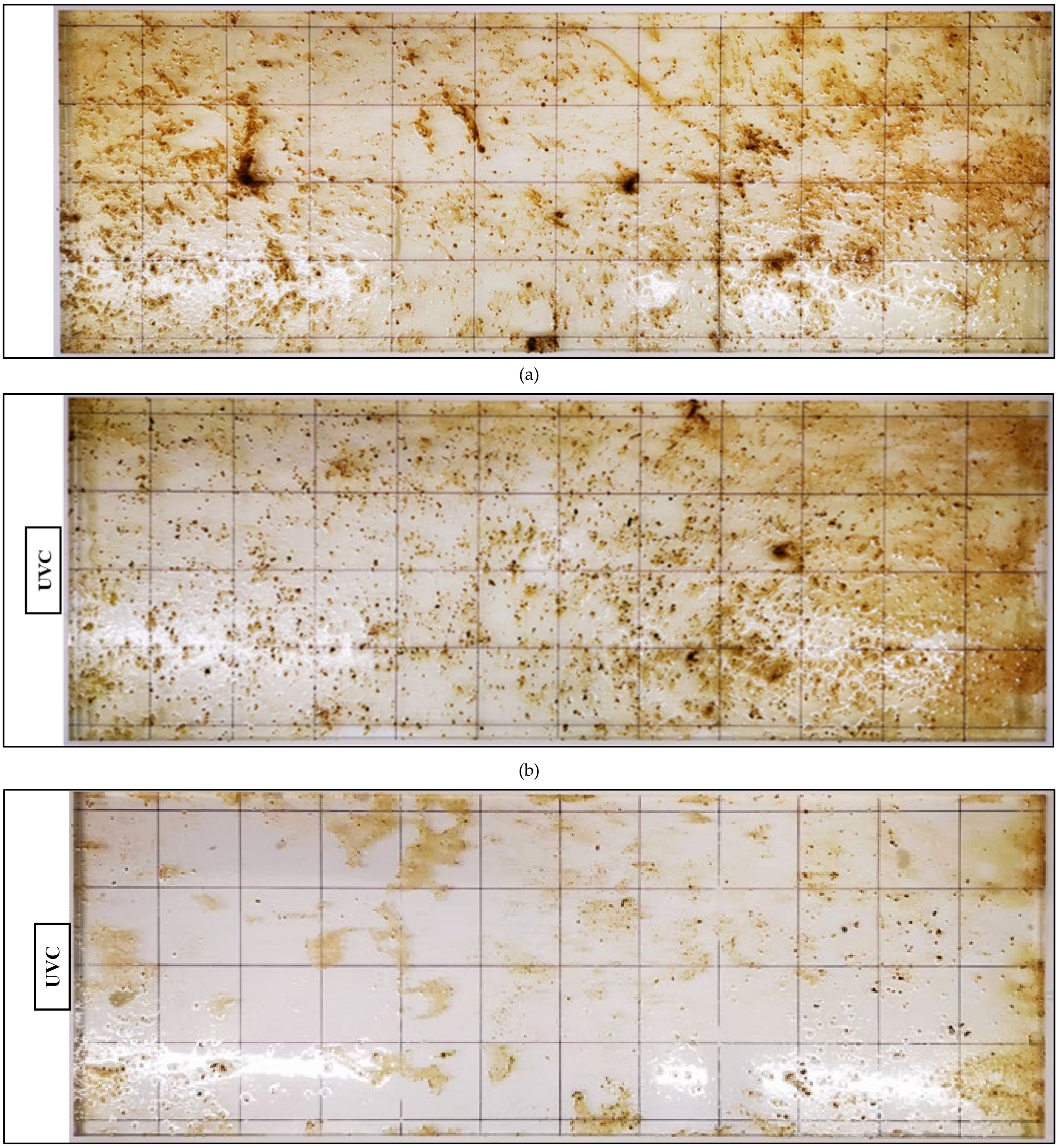
As with the previous tests, the control surface had 100% plate fouling coverage by day 14 (Fig. 11 (a)). The UVC was activated from day 15 and Fig. 11 (b) shows the plate at day 21. The biofilm was found to be partially dissolved and detached from the surface. This is because the final stage of biofilm development is the detachment of microbes and cell dispersal into the environment[51]. This is an essential stage of the biofilm life cycle that contributes to biological

(a)



(b)

Fig. 6 Biofilm observations (position 2): (a) Biofilm distribution over surface test surface during cultivation process at Day-14 (b) Biofilm distribution over surface test surface during cultivation process at Day-21, the detachments can be observed




(a)

(b)

(c)

Fig. 8 Biofilm distribution day 28 over testing surface (a) control surface (b) from arrangement of Position-1 (c) from arrangement of Position-2 with 1mm gap

dispersal[52]. The biofilm settlement by Day-28 over the control surface is given in Fig. 11 (a), from which biofilm detachments can clearly be seen.

For Position-1 arrangement, it can be found in Fig. 12(b), although the UVC was recommissioned after 14 days biofilm development, a 200mm × 200mm of biofilm destruction area can still be identified close to the LED. This test demonstrated that projected UV irradiation does have the ability to keep surfaces foul free even on an existing biofilm.

For Position-2 results, shown in Fig.12. (c), it is not really possible to identify how much biofilm protection is provided by UVC irradiation verses that which naturally occurs in the small gap at this stage. Detachment has long been considered the primary process that limits biofilm accumulation and occurs when external forces become sufficiently high or alternatively too low to maintain the biofilm structure[53]. However, regulation of growth and nutrient limitation may play an additional role. Due to the extreme low water exchange from the tank into the 1mm channel, the biofilm detaches from the surface probably due to insufficient nutrition and a high level of metabolic waste.

## IV. Conclusion

The fundamental principle of fouling prevention within a prototype power generator by projecting UVC light from the day of submersion has been investigated. The findings indicate that UVC light can effectively control biofilm to a radius of 288mm without relying on antifouling coatings and chemical usage. Where the UVC was activated only after 14 days of submersion, UVC is shown to be effective at reducing existing biofilm. Intermittent UV exposure with a sufficiently high-power intensity dosage was found to effectively prevent biofilm formation on submerged surfaces.

However, to understand and enhance the UVC antifouling efficiency, extra measurements and data are still required to understand the dosage in terms of power, exposure time and frequency, the transmission of UVC in seawater and the effects of water quality. Observations found the actual UVC light intensity may perform below the manufacturer's specifications, and this could also lead to a detrimental effect on its biofilm control performance.

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