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Assessing biofouling in Ocean Thermal Energy Conversion (OTEC) power plant – A review

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Assessing biofouling in Ocean Thermal Energy Conversion (OTEC) power plant – A review

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Abstract. Ocean Thermal Energy Conversion (OTEC) harnesses thermal energy stored at different seawater depths via power generation from a thermodynamic closed-loop cyclical system. Apart from its consistent energy generation, it could be diversified into other side industries, making OTEC an attractive and sustainable source of renewable energy. However, the process that utilises seawater as its main fluid is exposed to biofouling deposition due to unwanted growth and accumulation of biological elements on any contact surfaces, potentially affecting its efficiency and damaging equipment in the process. Considering that biofouling is an inevitable condition that may not be eliminated, a comprehensive study for assessing potential biofouling growth and deposition mechanism is a crucial step for strategizing effective biofouling management in a commercial and large-scale OTEC power plant facility. This review paper focuses on evaluating suitable biofouling assessment techniques specifically for a large-scale OTEC power plant facility. This is achieved by evaluating previous and proposed biofouling assessment techniques relevant to OTEC systems by focusing on their implementation under a realistic OTEC setup. The initial study indicated that the potential of biofouling deposition may be unavoidable in some sections in all OTEC models, despite biofouling-free design consideration. Previous OTEC biofouling studies were evaluated with reported physical and biological assessment approaches indicated the need to further improve these techniques especially in continuous and non-destructive methods. Therefore, several biofouling monitoring systems reported from other water treatment industries were considered for the OTEC systems, with findings indicated the importance of considering important OTEC operational parameters for feasible and robust biofouling monitoring systems. Two major parameters which are seawater intake flow rate and temperature variation at different seawater intake levels were evaluated under OTEC operational evaluation by considering examples of practices conducted in cooling water systems in the power plant industry. A realistic biofouling monitoring setup for mimicking continuous changes in biofouling deposition is required, in this case by side-connecting an operated OTEC power plant facility with a pilot plant setup or a side sampler. This step allows the application of proposed biofouling monitoring techniques under a realistic and uninterrupted biofouling deposition setup.

1. Introduction

Ocean Thermal Energy Conversion (OTEC) is a renewable source of energy that utilises the thermal gradient of the seawater at different sea levels by pumping warm water supply from the sea surface to generate steam that runs a turbine, while concurrently the cold water supply from deep seawater is used to cool down the outlet stream from the turbine for re-condensation [1]. Based on this concept, an optimum OTEC system could be achieved at the minimum sea temperature gradient of 20°C within the sea depth of 1000 m [2]. By considering the fact that the oceans absorb an enormous amount of solar thermal for about 4000 times than the presently consumed by humans [3], OTEC has wide potential to be exploited as a renewable source of energy. Apart from its capability as a continuous and base-load renewable energy generation [4], OTEC has the capability for producing energy up to 3 TW [5], where this number is estimated could meet twice of electricity demand worldwide. Unlike other sources of renewable energy such as solar and wind energy, the applicability of OTEC could be diversified to other industries such as deep seawater (DSW) and desalinated water generation, air conditioning system, aquaculture industries, hydrogen gas production, mineral extraction (i.e. lithium) from seawater and for cosmetic and high-grade food production [6].

In an example of a closed-loop OTEC system, the system operates when warm sea water obtained at the surface level is channelled to an evaporator to vaporize a working fluid in a closed-loop thermodynamic heat engine system, operated using highly-vaporized fluids such as ammonia or R-134a [1]. The evaporator converts the working fluid from liquid to high-pressure vapour flow where this vaporized stream is later used to run a gas turbine for power generation. The stream coming out from the turbine is then cold down by a condenser using deep-sea cold water intake, where the condensed working fluid is pumped and circulated back into the evaporator. The thermodynamic efficiency for about 3-5% could be achieved in an optimum OTEC system, subjected to the optimal temperature difference between hot and cold water temperature [7]. However, this efficiency might decrease by about 1-2% as a result of fouling that could take place inside the heat exchangers (evaporator or condenser) [8].

Huge interest for an alternative source of energy after the world major oil crisis in early 1970 saw large investment for about $260 million by the US federal government in OTEC research with an aim for generating 10,000 MW energy from OTEC by 1999 [9]. The following years (the 1980s-2000s) saw advancement and improvement in OTEC technology with the largest commercial-scale OTEC power production is 100 kW by the Makai OTEC power plant in Hawaii [10]. Large intake of seawater is proportionate to the capacity of OTEC power generation, where a hypothetical 100 MW capacity of OTEC is projected to use enormous amount of seawater for about 400 m^3/sec of warm feed water and 200 m^3/sec of cold feedwater [11]. In terms of Malaysian oceanic profile, the northwest and southeast of Sabah have been identified to be a suitable location for future OTEC development in Malaysia due to the availability of deep seawater greater than 1000 m with the average surface seawater temperature reported at 27°C and approximate temperature of 4°C at the depth of 600 m [12]. This location is projected could produce approximately up to 10 MW of OTEC commercial plant [12].

When considering a system that uses water as the main processing fluid, untreated and raw water contains various physical-chemical properties which directly affects any physical surface that is in contact with water. One such example is on fouling where it could occur as a result of deposition of matters that could disrupt the optimum flow of water in a processing system. This fouling problem could be contributed by various factors, whether scaling or crystalline fouling, organic fouling due to the deposition of organic matter, particle and colloidal fouling as a result of silt or clay deposition or microorganism fouling [13, 14]. Among all these types of fouling, biofouling is considered to be inimitable problem that is influenced by the properties of intake water to a system and optimum conditions, which eventually allow distinctive growth and deposition of microbes on a concerned material surface. Biofouling is the result of undesired deposition of all forms of biological elements on immersed materials [15]. A typical biofouling growth and deposition involve the microbial adhesion on the exposed surface, where the accumulation of microorganism forms aggregates biofilm and the colonization of macrofouling species on the surface of the biofilm layer which is enriched with nutrients and protected from biocides and toxins [16]. The prolonged colonization process allows the attachment and growth of invertebrate larvae and the spores of algae on the submerged surface [15]. Among these macro biofouling species are such as barnacles, mussels, sponges, sea anemones and hydroids, bryozoans, serpulids, algae and others [15]. The final stage of biofouling occurs when the matured biofoulants are accumulated on the surface and in the flowing stream, these biofoulants could be detached from the substrate. Figure 1 illustrates schematic stages involved in biofouling growth and deposition on the exposed surface.

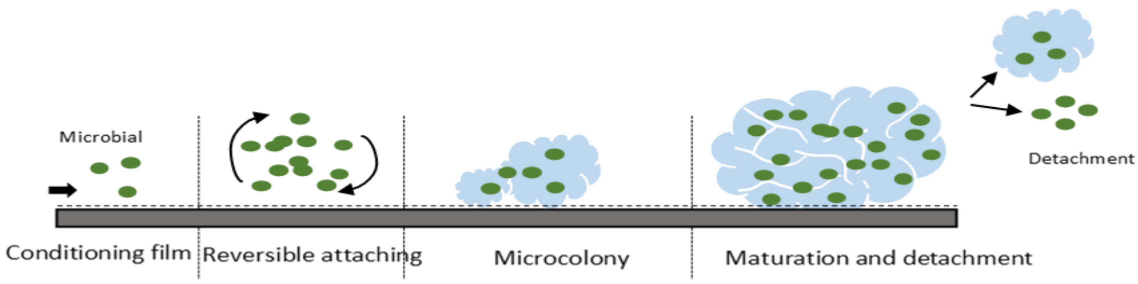

Figure 1. Stages involve in biofouling growth and deposition on an exposed surface [14]

Biofouling poses a major problem in this facility due to its potential deposition on the surface of heat exchangers, reducing the efficiency of heat transfer between seawater and working fluid streams. For example, the presence of a thin biofilm of 25-50 micrometer could reduce the performance of OTEC by 50% [8]. In addition, biofouling deposition particularly for severe macrofouling depositions along the internal wall of contact surface may increase pressure drop inside the heat exchanger and seawater pipelines, as well as impairing the performance of associated auxiliary systems. Apart from that, large deposition of macrofouling which is classified as large-size and distinctive invertebrate larvae and the spores of algae [15] may potentially restrict water pipeline, increasing additional weight to a floating OTEC facility and in the worst condition, might cause serious damage to the processing facilities [17]. The presence of biofouling is also associated with microbially induced corrosion (MIC) where biofilm adhesion on a surface changes the electrochemical interface properties thus inducing corrosion [18].

The earliest study of biofouling in Malaysia was done by Cheah and Chua [19] who recorded more than 34 species in floating net-cages structures such as oysters, algae tunicates and mussels. Relating this outcome with the OTEC potential site in Sabah, Affandy, et al. [20] and [21] conducted two relevant studies on the development of macrofouling at the shallow coastal area of Karambunai Bay. The studies found out that thirteen different biofouling species (sessile and mobile) were identified on submerged PVC plates (2 m x 8 m) throughout their observation in 180 days. These biofouling communities had a significant relationship with environmental factors, in this case, average seawater temperature was recorded within 29.9°C to 30.9°C and low net current speed from 5 cm/s and 7 cm/s.

There are two major focuses of the biofouling management system which are biofouling assessment and detection activities as well as biofouling controlling measures, where in this report, focus will be on adopting continuous and online biofouling monitoring systems. A reliable and robust biofouling detection system provides crucial information of biofouling characteristic profiles either biological or physico-chemical aspects and most importantly, the degree of biofouling deposition at several important sections in the OTEC facility. For example, in the design and engineering aspect, the usage of oversized heat exchangers which intended to provide a large heat transfer area under the anticipation of biofouling deposition may be re-evaluated with prior understanding of the expected severity of biofouling. In addition, continuous assessment of biofouling deposition serves as a guideline in optimum biofouling controlling measures. In this case, the usage of overdose chemical biocides using high-dosage chlorine could be controlled for effective inhibit biofouling deposition [8] as a result of improvement in continuous low-dose chlorination monitoring activity. Despite the importance of acquiring a biofouling monitoring system, current practices in the water-related industries are based on visual inspections and a long period of assessment, albeit that the biofouling growth and deposition are physically undetectable in normal conditions and rapidly changing over a period of time.

Considering the requirement of minimum temperature difference at 20°C and its small efficiency of about 3 to 5 percent [7], feasible maintenance and operating practices in OTEC power plant facilities specifically for managing any biofouling deposition are essential to ensure its consistent potential power generation on a commercial scale. This is crucial for the preparation of operating commercial scale of OTEC facility where any small change in its operation could eventually affect the whole OTEC efficiency. In the following report, focus will be on the biofouling assessment methods and techniques which accommodates commercial and large-scale operation of the OTEC power plant facility. The manuscript consists of a few sections: 1) Overview on several OTEC models and design consideration for potential biofouling deposition 2) Previous reports on biofouling assessment in OTEC system; 3) Potential application of advanced analytical instruments and sensors for detecting biofouling growth and deposition in operated OTEC facilities; 3) Operating aspect for biofouling assessment and 4) Setup for biofouling assessment activities.

2. OTEC model systems and biofouling design consideration

As the demand for renewable energy is expected to increase due to the concern of global warming, it indirectly opens up the opportunity for a feasible and large-scale OTEC power generation, pending the reduction in its overall operational costs [22]. The high operating cost of OTEC is estimated at $40 million per annum [22], contributed partly by the huge pumping cost for transporting large flow rate and low-pressure head of cold deep seawater [23], which consequently contributes to OTEC overall thermal inefficiency [22]. By minimizing biofouling deposition in intake pipelines, indirectly improves the optimal flow rate of seawater intake due to minimal drag force caused by hard-shell biofouling deposit, which ultimately improves OTEC performance. Therefore, the understanding of potential biofouling deposition in OTEC design helps in determining suitable biofouling assessment programs, where this could be achieved by considering various OTEC models and their general process description, as well as ecological factors, specifically in the Malaysian marine environment.

Generally, there are three different OTEC models available on both commercial and laboratory scales: closed systems, open systems and hybrid systems. The closed OTEC systems generate energy by using a closed-loop refrigerant cycle which normally contains ammonia that is vaporized through warm surface seawater before it is passed to a turbine for power generation before cooling it back to liquid refrigerant using cold seawater intake. Different configurations of heat exchangers and turbines for the closed-OTEC system have been proposed for achieving high efficiencies such as first-model of Rankine-based cycle [24], Kalina cycle [25] and Uehara cycle [7]. On the other hand, open-cycle OTEC systems use seawater as a working fluid to generate power in OTEC facilities via rapid flashing of the warm seawater under a low-pressure vacuum chamber [26]. As for hybrid-OTEC systems, the systems which combine both a high-efficiency closed-loop system and an open-OTEC system allow both power generation as well as other side-product production such as high-throughput potable water production [27]. Etemadi, et al. [28] reported that the hybrid cycle uses both seawater and working fluid such as ammonia, fluorinated carbons or hydrocarbons in hydraulic and vapour turbines. The phase change of the water/ammonia vapour in this process turns a turbine producing energy. Even though the selected working fluids used in the process possess qualities due to their excellent transport properties, easy to obtain and low cost but they have a few setbacks due to their flammability and toxicity which might result in both safety and environmental issues. Moreover, the pressure of the liquid used strongly affects the size of the OTEC system, as the high pressure decreases the size of both the turbine and the heat exchangers, which inversely requires thicker wall thickness [29].

The Malaysia hybrid OTEC is the latest OTEC system that has function as power generation and desalinated water production systems [12]. This hybrid OTEC system indirectly uses surface seawater, converts it into vapour in the heat exchanger to produce electricity and at the same time, freshwater can be produced through distillation. A simplified process flow diagram for the hybrid OTEC is illustrated in figure 2. In this system, a vacuum chamber will quickly evaporate warm seawater. The water steam will cause a working fluid to reach its boiling point. Then, electricity is generated by expanding the refrigerant in the turbine, followed by the vaporized fluid condensing inside a heat exchanger, thus generating desalinated water [30]. According to Magesh [31], the hybrid OTEC system is capable to generate nearly 2.28 million litres of desalinated water every day for every megawatt of power.

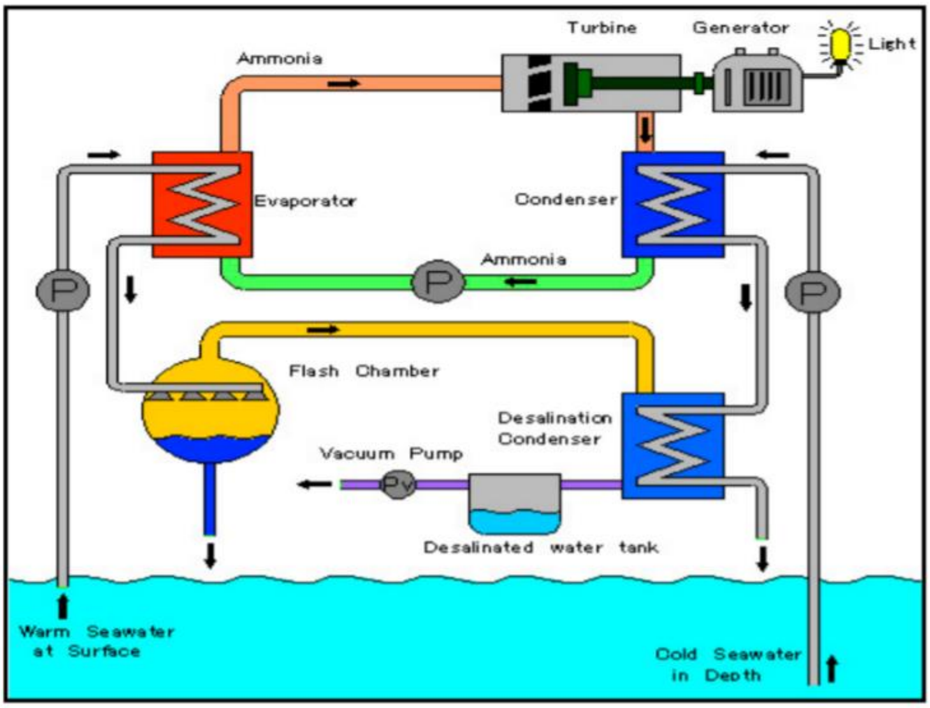

Figure 2. Process layout for OTEC Hybrid cycle with desalination process [32]

Depending on the design of OTEC systems, potential biofoulants that deposit on the surface of heat exchange is inevitably affecting overall efficiency especially an OTEC model that adopts direct-contact seawater heat exchangers for condensers and evaporators. However, a recent study conducted in 2013 reported that a free-biofouling design has been considered since the 1980s, in this study, a brazed aluminium heat exchanger was incorporated in this feature, and currently being used in the Makai OTEC power plant [33]. This biofouling preventive consideration is made possible particularly in a hybrid OTEC system where the heat exchanging process uses vaporized seawater stream generated from a vacuum chamber, thus decreases serious consequences of biofouling in OTEC heat exchangers. This new design feature eliminates the concern of the threat of biofilm in heat exchangers. However, even with this new feature of heat exchangers used in OTEC system, deposition of macrofouling may still unavoided particularly in intake pipeline system for warm surface seawater. In addition, processing units such as strainers, pumps, holding tanks and pipeline fittings are among a few types of equipment in the OTEC power plant that are still exposed to potential biofouling deposition.

Based on the above explanation, it is crucial for OTEC operators to evaluate biofouling in any type of OTEC system used as the exposure to any potential biofouling is almost inevitable. This could be done by exploring any reported techniques used for assessing biofouling specifically for OTEC systems which will be highlighted in the next section.

3. Previous reports on OTEC biofouling assessment

The concern in biofouling study in OTEC is comparative to the interest and advancement of OTEC over a period of years with most of the reports on the assessment of biofouling in OTEC facilities have been initiated since the late 1970s to mid-1980s [8, 15, 34, 35, 36]. These reported techniques were implemented in actual OTEC facilities or the mock heat exchanger for representing close to the actual condition. For example, Berger and Berger [8] conducted their study in Seacoast Test Facilities at Ke-aholes, Hawaii. Likewise, Panchal and Knudsen [37] conducted a similar analysis at the same facility specifically for determining potential biofouling in tropical water. In contrast, Aftring and Taylor [36] explained in detail their biochemical assessment of biofouling formed on the mock heat exchanger to mimic the actual condition of OTEC condition. The assessment conducted in fields provides realistic representation on biofouling growth and deposition, thus acquiring suitable biofouling evaluation techniques in their setup. Two broad categories of biofouling assessment techniques that were reported under previous OTEC setups are presented here, namely physical and biological and biochemical approaches. The following subsections explain the concept of these techniques, their advantages and their limitations in the current OTEC setup.

3.1 Physical assessment

This method focuses on detecting and analyzing any physical changes that take place due to the presence of biofouling growth and deposition on exposed surfaces. The first method uses a heat transfer monitoring (HTM) device for determining the thickness of micro fouling that is appeared as a thin layer of biofilm on the surface of the pipeline wall. Based on the concept of heat transfer measurement, the thickness of biofilm that acts as heat transfer resistance is measured by measuring the temperature difference between the heated section of fluid inside the pipeline and the reference temperature, in this case at ambient temperature [8, 38, 39]. The apparatus consists of two thick-walled sections of copper cylinders, one section that acts as ambient temperature measurement and another section is a heated wall surrounded by a nichrome heater. These cylinders are inserted inside a section of the pipeline whereupon continuous seawater flow, the presence of biofilm is detected through changes of measured temperature difference.

This method is applicable when the flow velocity is within 2 to 8.4 ft/sec with high sensitivity of temperature difference is about 0.001°F [38]. Berger and Berger [8] reported that the application of HTM by observing the change in fouling resistance (R_f), recorded within R_f of 8 to 10 × 10^5 °C/m^2 ·W for about a three-year continuous observation period. However, this device is designed for assessing biofilm thickness in the pipeline and may not be suitable for tubing in a heat exchanger [15]. Moreover, the thickness of biofilm is practically accessible within a short span of the pipeline due to the limited length of the device and may be able to describe accurately biofouling deposition due to its spatial deposition profile on the surface [40].

3.2 Biological assessment

Scanning electron microscopy (SEM) is used to analyze biofouling growth and deposition profile on the contacted surface, providing crucial information of the type of organisms or materials involved, a rough estimation of biofilm thickness and the nature of its growth [15]. Before this visual inspection, the accumulated biofouling sample on a set of attached coupons to the surface of a heat exchanger was extracted by scrapping manually by cutting out a section of the heat exchanger tube [8] or using a special tool to scrape any deposit on the surface of heat exchanger [41]. These coupons were subjected to accumulate biofouling deposition over a period of time, in the report mention by Berger and Berger [8], it was done within six months up to one year before the samples were extracted. The extracted samples formed a biofilm layer comprised of entrapped diatoms and portions of differentiated algae and other organisms. Apart from determining the species present on extracted substrates, this technique evaluates the effectiveness of mechanical cleaning techniques by observing any residual that remains after the physical cleaning process using either sponge rubber balls or bristle "test tube" brushing methods [8, 15] as well as after chlorination approach for retarding microfouling growth [8]. Despite these efforts, the presence of biofilm was still observed after three-year of observation and preventive period [8]. The applicability of SEM is still relevant even in the presence of OTEC setup, however, the destructive method for extracting sample may provide unpresentable biofouling deposition profile on substrates.

Besides the semi-quantitative measurement of SEM, the availability of various biochemical assessments provide a comprehensive biological and chemical characterization of the extracted sample. There are a few biochemical assessments that have been reported under the scope of OTEC systems [15, 36, 42]: adenosine triphosphate (ATP) total organic carbon (TOC), carbohydrate analyses, chlorophyll contents, total dissolved iron content, combustible organic matters and many others methods. Mitchell and Benson [15] and Aftring and Taylor [36] are among the earliest studies of biochemical assessments conducted specifically for OTEC in the 1980s. Among those measurements was the ATP test which detects the concentration of a growing microorganism as ATP is a molecule that could be found in any living cells [15]. Apart from ATP, the TOC measurement that indicates the total nitrogen content and protein that made up the composition of biofilm was also reported in these reports [16]. The measurement of carbohydrates and chlorophyll reported by Aftring and Taylor [36] indicates the presence of organic compounds that promote the bacterial growth of biofilm [43]. Acknowledging the importance of various biochemical assessment which provide quantitative measurement of biofouling sample, the setback of this approach is due to the absence of standard measurement gives discrepancy and inconsistency in reporting severity of biofouling [43]. Moreover, these measurements are only accessible under extensive laboratory procedures and may not be effective in describing constantly-change biofouling growth and deposition profile

The establishment of both physical and biological assessments form the fundamental techniques in assessing biofouling problems, particularly in the OTEC system. However, substantive information that describes biofouling deposition under the actual field parameters is crucial for describing accurately the severity of this deposition, as summarized in figure 3. Factors such as the flow velocity, the physical design of the system, the variation of seawater temperature and the exposure time with seawater are some of the important criteria that need to be considered under the engineering perspective. Considering the several reported biofouling assessment techniques, an improved and reliable biofouling assessment approach is needed, in this case using a continuous, non-destructive and online biofouling detection system. The following sections describe the application of the various analytical instrument in assessing biofouling.

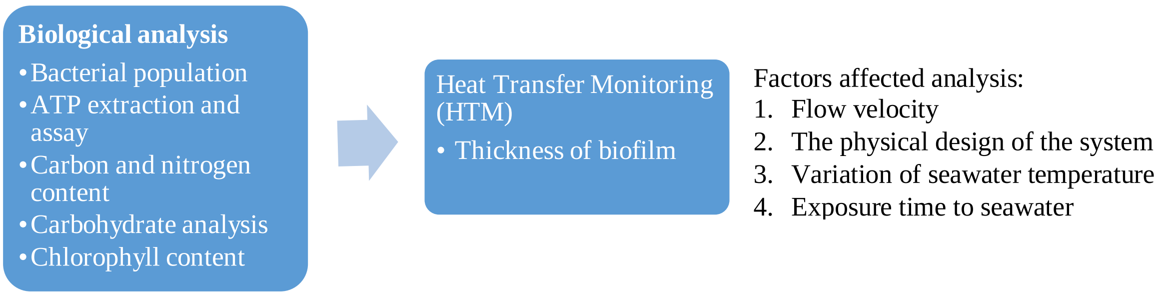

Figure 3. The overview of biofouling assessment techniques conducted in OTEC facilities

4. Potential biofouling assessment techniques

A flexible and effective biofouling monitoring method is required with a focus on several qualities of the continuous, non-invasive, online biofouling detection system, in this case, is based on several studies conducted in membrane distillation (MD) technology used in desalination and water treatment. Several manuscripts have extensively reviewed these methods and techniques under the scope of MD application [13, 14, 16, 44], with most of them are relevant and applicable to the OTEC technical setup. Acknowledging the importance of various applications of analytical instruments in a laboratory setup, this report focuses on identifying suitable monitoring assessments that are suitable under field application. A list of suggested analytical instruments and techniques are presented in table 1, suggesting advantages and setbacks for their implementation under OTEC process conditions.

Although most of these instruments are superior in term of their accuracy and detection in the system, most of them are only applicable in laboratory setup where ex-situ assessment is adopted. Despite its convenience and environmental-controlled laboratory setup, imitating actual conditions for the growth and deposition of biofouling is a challenging task due to complex and constantly-changing environmental factors which are almost non-viable to be replicated under laboratory setup. Even when the scale-up procedure or the modelling and simulation could be implemented, the absence or limited data of biofouling assessment from actual field conditions may overestimate the problem. For example, the variation of nutrient and temperature with respect to different depths of seawater and variation of biofouling deposition with respect to a rapid and constantly changing flow rate of seawater and the size of the deposited section may give measurement far from the actual condition. Several reports documented the usage of analytical instruments in the actual field such [16, 45], but their feasibility to withstand constantly changing environment are yet to be accepted by the industry.

The limitation for implementing suitable biofouling detection system is resolved with the well-addressed parameters that directly control the performance of actual OTEC systems. Therefore, the following section explains factors that contributes to the observation of biofouling in a real OTEC power plant facility.

Table 1. Techniques used in the evaluation of complex biofouling phenomenon

Technique	Concept	Techniques	Advantages
Microscopic and optical techniques	Visual-aided technique to magnify the image of deposited biofouling.	1. Optical coherence tomography [46] 2. Fiber optical sensor (FOS) [47] 3. Differential turbidity measurement (DTM) [48]	1. Ability to detect thin biofouling on a surface Practical techniques with improved features
Spectroscopic	Based on the absorption, scattering or emission characteristic of a matter subjected to the emitted light	1. Raman spectroscopy [49] 2. Fourier Infrared Transform (FTIR) 3. Nuclear Magnetic Resonance (NMR) [50] Photoacoustic spectroscopy	1. High accuracy with an almost negligible amount of required sample 2. A non-invasive and non-destructive method Ability to measure biofilm inflow velocity profile (NMR)
Physical assessment	Changes in physical characteristics in operating conditions with respect to the presence of biofouling	1. Pressure drop detector Heat transfer monitoring system [8]	1. Practical and readily implemented in fields 2. Cheaper Ability to withstand an extreme environment

Electrical techniques	Using electrical techniques to detect biofouling	1. Electrochemical sensors: (a) chemical potential measurement, (b) microelectrode for measuring the chemical concentration 2. Piezeoelectric [44] Electrical impedance spectroscopy [51]	1. Time-dependent measurement Ability to detect chemical profiles on the interface.
Biological/ chemical detecting techniques	The on-line monitoring system that adopted biological or chemical sensors for biofouling detector	1. Measurement of metabolic products at biofilm layer [52] 2. Low-concentration diffusible molecules (LCDMS) [53] Electrochemical sensors that detect changes in the interfacial chemistry due to biofilm activities.	Advanced technique that requires simple detectors condition

5. Assessing biofouling in OTEC power plant facilities

Assessing biofouling in an OTEC facility requires an adequate understanding of operating parameters that are subjected to OTEC process specifications. This requires continuous monitoring since any parameter changes that take place inside the system require effective remedies and minimize excessive usage of harmful chemicals for the preventive approaches. As the basis of this study is mostly based on operational aspects of cooling water systems in power plant industries [17], the primary aim of the biofouling monitoring system is to ensure minimum deposition on crucial sections of the OTEC system, in this case at the surface of the heat exchanger as well as seawater intake pipelines. The understanding of these potential factors allows the OTEC plant operator to assess any potential location which likely to form biofouling and possibly for installing online monitoring detectors. There are almost no reports discussing specifically biofouling problem in operational point-of-view. However, this assessment could be done by correlating with a few cases related biofouling operational assessment in cooling water process system that is used power plant industries. This is mainly due to similarity in term of process specification which involves cooling or heating processes using heat exchangers and large usage of natural water obtained from oceans, rivers or lakes [17].

Macrofouling organisms are expected in operational biofouling observation as these organisms are more noticeable in terms of the size and the potential impact on a subjected facility than the microfouling. The degree of fouling is expected to be higher as the apparent seawater usage in the system than a system that uses freshwater sources. The settlement rate of biofouling could take a few hours and up to about 400 hours [17]. However, other parameters may influence the biofouling in biofouling growth and deposition, classified into chemical, physical and biological parameters [54] as shown in table 2. Two main parameters are highlighted in section which are flow rate of seawater intake and temperature of seawater intake as both are the two major parameters that have significant impact to the operability of the OTEC power plant [35].

Table 2. Parameters involved in experimental setup for biofouling assessment [54]

Chemical Parameters	Physical Parameters	Biological Parameters
Substrate type	Temperature	Microorganism type
Substrate concentration	Fluid shear stress	Culture type (mixed or pure)
pH	Heat flux	Suspended cell concentration
Inorganic ions	Surface composition	Antagonist organism
Dissolved oxygen	Surface texture	
Microbial inhibitors	Fluid residence time	

5.1 Flow rate of intake seawater

The rapid flow of water provides sufficient oxygen and nutrients for the growth of macrofoulants, thus propagating colonization of macrofoulants. In contrast, the sea water flow which is under restricted flow condition and well below its critical velocity profile may accomodate fouling inside the processing system [35], thus it is difficult to correlate the relationship the velocity to the biofouling growth and formation. There is possibility of the hindrance of biofouling settlement at rapid flow due to the high shear rate of water than the shear rate of the settlement. However, a typical flow rate of water at 1.4-1.8 ms^{-1} across the heat exchanger and 2-3 ms^{-1} through inlet pipelines does not prevent the settlement of biofouling [17].

The observation of biofouling in operating condition is often observed inside a heat exchanger as well as in sea water intake pipelines. The accumulated biofouling over a period of time increases thickness of biofouling up to 30 cm from the wall [17], causing blockage to the internal section of a direct-contact sea water heat exchanger, as shown in figure 4. Under such condition, the presence of biofouling in the heat exchanger could be detected by assessing the reduction of heat transfer, where the fouling acts as heat transfer resistance as well fluid frictional resistance [55]. Conversely, biofouling accumulation in pipelines could be done by measuring pressure loss in the flowing system [54]. The presence of biofouling detector may not guarantee full assessment of biofouling as the detector might not be able to distinguish other elements of fouling such as deposition of inorganic compounds such as scaling and corrosion. Therefore, Jenkins [35] has suggested to relate the relationship between shear effect due to velocity with the effect of corrosion. The placement of biofouling detectors could be strategically positioned in biofouling-prone sections by considering mechanical and environmental design factors related to OTEC power plant facility.

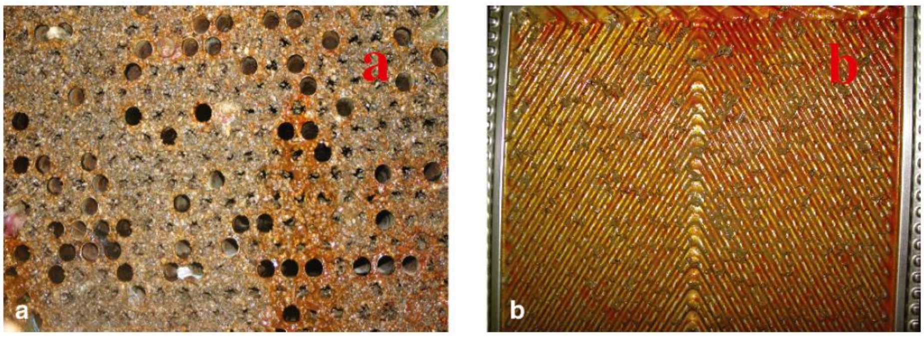

Figure 4. Examples of blockage of biofouling and corrosion in a tubular heat exchanger (**a**) and plate-fin heat exchanger (**b**) in a power plant station [17]

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5.2 Variation of temperature at different sea water level

The variation of the temperature profile in an OTEC operating system depends primarily to the depth of seawater intake, where a uniform warm surface seawater temperature at 28ºC is typically achieved within 35 to 100 m before it reduces gradually to 4.4ºC at the sea depth of 800 to 1000 m [56]. The potential of biofouling growth and accumulation is likely to be higher in tropical seawater environment [17] where constant temperature throughout the year provide steady development of biofouling community than the seasonal-change seawater area [20]. Under OTEC process specification, it is expected high potential biofouling growth and accumulation could take place in the warm surface seawater intake than the deep cold seawater intake [15, 35]. The warm surface seawater exposed to continuous sunlight favours the growth of biofouling, with different potential biofouling that exists at different sea levels [15]. A sea water temperature ranged between 20ºC to 50ºC is considered to be the optimum temperature for microbial growth with the ability of the microorganism to survive in a wide range of temperatures [37].

Factors such as the location of the OTEC power plant to the location of both warm and cold seawater intake, the size and length of the pipeline as well the amount of heat loss to the surrounding (particularly for cold seawater intake) relative to the length of pipelines indirectly affect the temperature profile of transported seawater, thus subjecting OTEC plant facility with different severity of biofouling deposition. For example, potential biofouling is expected to be higher in onshore facilities than offshore facilities due to the high concentration of organisms near to onshore area [56]. Additional processing units such as desalination and depressurization units which involved along with the main OTEC system may have a significant impact on the flow rate and temperature profile of the system.

6. Setting up environment for biofouling assessment

As much as biofouling detection techniques are concerned, it is essential to evaluate the biofouling under a realistic setup where biofouling could form. Implementing directly these detection techniques in an operating OTEC system is almost impossible due to strict and delicate process requirements, albeit similar problem is faced in laboratory-scale setup due to limitations in imitating the same actual setup and parameters for replicating biofouling deposition. Despite their limitation compared to the actual scale, the laboratory scale data provides a practical solution for assessing the effectiveness of several biocides and other biofouling controlling measures before it could be implemented in actual operating conditions. This could be achieved when considering several requirements to grow the biofoulants in a suitable medium, nutrients and parameters (i.e. temperature, oxygen, salinity, pH level and others), as well as the representation of shear stress of the biofoulant on the contact surface [54]. This could be represented on various scales, ranging from a bench-scale flow cell known as Robbin device [54], a medium-scale flow loop consists of a controlled-process pipeline setup [57] and a dummy heat exchanger setup that is connected to an operating facility [36].

It is favourable to have an in-situ monitoring device which can measure realistic operating condition over a period of time without interruption. One of such options for this is by using a side stream where the water from the OTEC facility is passed through pipelines that represent the same design characteristics (i.e. roughness of the surface, size and materials) and operating parameters [17]. Current practise in monitoring the growth of fouling organisms inside cooling circuits at the power station is by using biofouling monitor which consists of a chamber with removable test panels. For example, the usage of an aquarium-like box as a side-stream sampler such as Bio-box and KEMA Biofouling Monitor® (presented in figure 5) is used to mimic the flow of industrial pipeline condition and strategically located at biofouling-prone section such as intake pipelines [58].

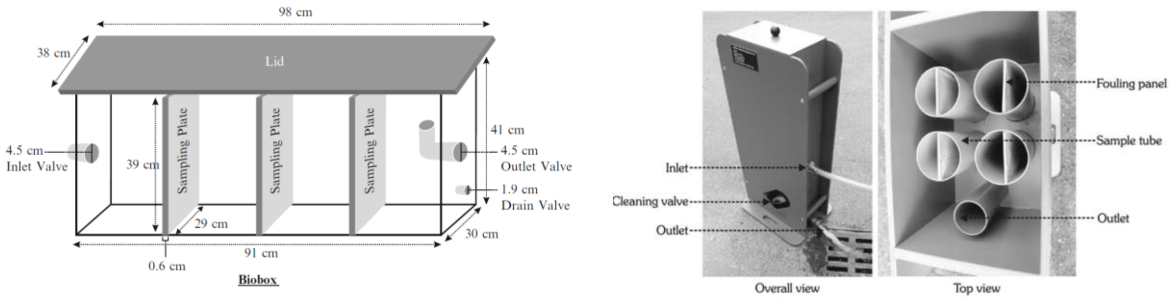

Figure 5. Illustration of (a) Biobox and (b) KEMA Biofouling Monitor [58]

Another option is to build a pilot plant scale process system that could explore all possible parameters where the biofouling deposition could occur close to the actual process conditions [54]. Despite additional technical consideration and cost, these two setups are feasible for evaluating potential biofouling deposition and the effectiveness of using biocides in the close representation of actual conditions.

7. Conclusions

Previous biofouling assessment techniques conducted in OTEC systems showed their reliability in monitoring the realistic condition of biofouling deposition, contributed by their application in an actual OTEC system. However these methods are lack continuous and non-destructive assessment, thus minimizing evaluation on progressive evaluation in biofouling deposition. Therefore, advanced biofouling detection techniques from other water-related industries could be employed in the OTEC system, with emphasis on its feasibility for its implementation in actual OTEC process setup. In this case, the operational understanding in biofouling assessment for OTEC power plant facility is crucial for designing practical and realistic implementation of the proposed biofouling detection techniques, in this case, based on practices done in the cooling system of power plant industries. Two main parameters which are flow rate and the seawater temperature variation are considered in this study, along with factors contributed by physical design and environmental factors concerning the OTEC power plant facility. However, a thorough evaluation of biofouling assessment could only be done under realistic and continuous biofouling growth and deposition setup. In this study, laboratory setup was found to be a practical approach in assessing the capability of analytical instruments inconvenient and small-scale setup, but limited in representing realistic biofouling deposition. Therefore, the application of a side-stream sampler or pilot plant facility that is connected to an OTEC facility provides the opportunity for evaluating realistic biofouling conditions without affecting the OTEC system.

8. References

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