Optical glass micro-fibre based transducers for dissolved oxygen sensing and monitoring: an overview

M S Shamsudin1,2,3,a, H H J Sapingi1,2,b, M S A Aziz1,2,c

1Laser Centre, Ibnu Sina Institute for Scientific and Industrial Research, Universiti Teknologi Malaysia (UTM), 81310 Skudai, Johor D.T., Malaysia
2Department of Physics, Faculty of Science, Universiti Teknologi Malaysia (UTM), 81310 Skudai, Johor D.T., Malaysia
3School of Engineering, Faculty of Engineering and Physical Sciences, University of Southampton Malaysia (UoSM), 79200 Iskandar Puteri, Johor D.T., Malaysia

aCorresponding email: msshamsudin@graduate.utm.my
bCorresponding email: husnihani@utm.my
cCorresponding email: safwanaziz@utm.my

Abstract. Every single day, a large amount of fish dies from infection such as hyperoxia-induced gas bubble disease consequences by unusual dissolved oxygen (DO) level due to the natural occurrences and human-caused processes of supersaturated water. We are concentrating on the issue of sustainability – an issue of great importance and where this interdisciplinary area has the potential to make a profound impact. We need to step up our game by introducing DO sensing and monitoring at a large scale to overcome this global environmental issue. DO is known as oxygen saturation, one of the most critical parameters in accessing water quality, and necessary to be kept at a sufficient level for the survival of many forms of aquatic biodiversity. Hence, this review article mainly focuses on the potential of optical glass micro-fibre transducers for DO sensing and monitoring, and its contribution toward water security impacts - as part of the Sustainable Goals Development blueprint. The growing body of literature associated with five main work packages i) research motivation of water security, ii) research market analysis discussing the perspective on size, share, growth, trends, and forecast, iii) typical approach on characterising DO level as compared to the optical glass micro-fibre based transducers, iv) conventional design of the optical glass micro-fibre based transducers and v) mechanism of light modulation characteristic in the optical glass micro-fibre based transducers, are highlighted in order to gain a better understanding on the development and progress of optical glass micro-fibre as a transducer for DO sensing and monitoring that can change our life for the better. Finally, several recommendations for future work are presented at the end of this study for the reference of future readers.

1. Introduction

Dissolved oxygen (DO) or oxygen saturation is defined as the number of free oxygen molecules within the water, and to be specific the oxygen that is not bonded to any other element, or non-compound oxygen present in water. DO is one of the most important metrics in accessing water quality after pH level, turbidity, temperature, and many more because of its influence on the organism living within the body of water. DO is necessary to be kept at a sufficient level for the survival of many forms of aquatic biodiversity. For example, fishes need oxygen for respiration at all the time, while invertebrates,
bacteria, and plants require oxygen for respiration when there is no light for photosynthesis. How does DO exist? There are two methods in explaining how DO does exist - DO may enter the water through the air, and as a plant byproduct of aquatic photosynthesis. From the air, oxygen moves slowly diffuse across the water surface from the surrounding atmosphere. The overall chemical equation for the type of aquatic photosynthesis that occurs in plants is shown in Equation 1. From Equation 1, a plant byproduct of aquatic photosynthesis, which is free oxygen molecules is expected to be DO in the water. In addition to this, aquatic photosynthesis is light-dependent, where typically DO level will peak during daylight and decline at night [1].

\[
\text{light} \quad 6\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \quad (1)
\]

However, the amount of DO needed varies from creature to creature in the water. The natural mortality due to infection such as hyperoxia-induced gas bubble disease or gas embolism in fish has been recognised as a critical problem since at least the 1960s [2]. The term ‘gas supersaturation’ is used to describe an excess of any gas in water in which aquatic life is kept, and occurs when the total pressure of gases dissolved in water is higher than the ambient atmospheric pressure above the surface of the water. The early findings on the description of the signs and characteristics of gas bubble disease consequences by unusual DO levels were first described in 1904 [3]. The excess gas in the form of supersaturation is a precipitate formed from oxygen gasses within the water. They tend to collect on the external surfaces of fish. Under the condition of supersaturated water, bubbles collect on the external surfaces of fish only in a few seconds, and increase in size and envelop a fish completely within 10 minutes. After 1 to 2 days of a continuous flow of concentrated DO level, external gaseous lesions may be produced – a region in tissue in the skin, fins and mouth cavity which has suffered damage through disease due to the inflation of mucous membranes. In addition to this, a serious injury conspicuous clinical sign known as ‘popeye’ produced due to inflation of membranes behind and within the eyeballs. In short, these external characteristics are only overt signs of gas bubble disease, but not usually to death. In this situation, they lead to a loss of equilibrium in water. In another case, internal bubbles may also cause death. The blood in the blood vessels and water surrounding the fish have a similar saturation point; therefore, the DO excesses are about equal in the bloodstream of the fish and water; due to osmotic pressures on both sides of the gill membrane tend to equalise. Gas supersaturation in the water is readily transferred into the bloodstream of the fish. As a consequence, various quantities of DO contained in blood vessels, ranging from a few small gas bubbles to larger gas bubbles. For example, distend the heart bulbus (bulb-shaped anatomical structure) several times as compared to its normal size. The other sign of distress faced by the fish is part of the organ; auricle may continuously to beat but propels no blood. Under this condition, the fish’s body fluids become supersaturated, and excess gas is soon released internally in the form of bubbles. Hyperoxia-induced gas bubble disease described as consisting of vesicles of gas invading all the superficial parts of the fish such as eyeballs, fin, and in loose connective tissue of the orbits so that the eyes are forced from their sockets; less commonly bubbles beneath the lining of the mouth, in the gill arches, or beneath the skin, so that scales are raised from the surface. Then these bubbles circulate with the blood and grow in constrictions slowly. Because there is a continuous supply of dissolved gas that diffuses into the fish from the water, the process continues until blood circulation stops.

Several natural phenomena lead to gas supersaturation problem. An independent study conducted in 1975 [3] found photosynthesis by algae during bloodstream algae blooms has produced gas saturation of 250% in salt water, and 327% in freshwater. Therefore, the affected fish showed the characteristic symptoms of gas bubble disease, and death usually resulted from blockage of blood circulation in the respiration organs by the gas bubbles. Similar findings were reported in which photosynthesis activity also leads to gas supersaturation problems [5, 6]. In addition, other natural processes result in gas supersaturation due to ice formation, such as the physical barrier preventing the release of dissolved gasses as the liquid is converted into ice, as reported in the previous study in 1986 [7]. Therefore, as the ice forms, DO remains in the water. If DO cannot be released to the atmosphere, it may become...
concentrated in the remaining water, and cause gas supersaturation. A decrease in temperature in water may lead to gas supersaturation - even if the water is at an air equilibrium state that is 100% saturated with gas before the warming process begins. Mathematically, gas saturation levels may increase by about 2% for each decrease of 1 °C temperature. The temperature change may contribute to the natural occurrences of supersaturated water – in which temperature profile change could induce gas bubble disease in fish. Gas bubble disease developed when the water temperature decreased by only 3 to 5 °C. To make sure fish in good health condition, fish make vertical migrations from cold to warm water, corresponding to rich in non-bonded gaseous intermediate-concentration non-bonded gaseous behaviour. As observed by previous researchers in 1957 [8], fish migrating upward from a depth of 10m or higher would be at 130% gas saturation, during early summer to prevent gas embolism in fish. Similar findings were observed to support the evidence influence of temperature change in water resulting in gas supersaturation and gas bubble disease mortalities in fish [9-11]. However, in an isolated situation on a study conducted in 2019, Giomi and the research team [1] found oxygen supersaturation does play an essential role in protecting coastal marine fauna as their metabolic demands increase in response to the ocean warming especially in the Red Sea; warming rates faster than the global ocean average correspond to the warmest sea on the earth with mean temperatures up to 32 °C and regularly peaked up to 40 °C. In addition to this, photosynthetic organisms may release a high volume of oxygen during their daily routine photosynthesis activities that oversaturate the seawater up to 200 to 250%. This discovery can help to explain; the oversupply of DO created during the warmest part of the day that increases the thermal resistance or tolerance up to 3 °C of the associated cold-blooded species living within, protecting from heat events and higher temperatures.

In the following review, not only the oxygen supersaturation problem, but ocean deoxygenation may also threaten the survival of many forms of aquatic biodiversity, influences life processes from genes to emergent properties of ecosystems. Brief, oxygen continues to decline in some coastal areas despite substantial reductions in nutrient load, such as the level of chlorophyll that is sensitive to nutrient enrichment [12]. Again, as mentioned above, we raise DO necessary to be kept at a sufficient level for the survival of aquatic life. Breitburg and co-workers called for a ‘raised awareness’ of the oxygen-deficiency in ocean phenomenon [13]. Another environmentalist also supports it; Earle and co-workers [14] contended that such awareness must extend to all facets of society rather than the pages of scientific articles. In their argument, creativity such as interactive, intuitive, dynamic online maps and visualisations would be the door to generating the political and societal will toward the effective management needed to reverse ocean deoxygenation ultimately. The analysis, oxygen solubility level has declined in both open ocean and coastal waters modified by human activities that have raised global temperatures, greenhouse gas emission levels, and nutrient inputs, and the abundance and distribution of marine species have changed since 1950. In the recent trend, the global map indicated open and coastal sites where anthropogenic nutrients originating in human activities have exacerbated and already caused dissolved oxygen concentration declines to 63µmol per litre approximately to 2mg per litre. Global warming, which is an increase of global temperature, is primarily caused by potent greenhouse gas emissions such as nitrous oxide, methane, and many more [15], which are more damaging than carbon dioxide is considered the cause of ongoing ocean deoxygenation problem. Oxygen-minimum zones in coastal and the open ocean water have expanded by several million square miles at locations ranging from the northeast Pacific [16], northern Atlantic [17], to tropical oceans [18]. Decrease oxygen levels in both oceanic and the coastal area may reduce survival, maturing, and alter the behaviour of individual organisms [19-22]. Limit or halting ocean deoxygenation to restore oxygen to the previously well-oxygenated environment requires a local, national, and global efforts. There are three main vital criteria in the ocean deoxygenation management and policy strategic plan to achieve a well-oxygenated climate in both open ocean and coastal waters [13] such as by implementing i) ecosystem-based mitigation to restore and protect the environment, ii) adaptation to restore and protect fisheries and marine organisms, and lastly iii) DO monitoring and analysis program. At first, the actions needed to address ecosystem-based mitigation to restore and preserve the environment are human-made greenhouse gas emissions to the atmosphere need to be reduced and followed by the reduction of
anthropogenic nutrients reaching coastal water to minimise eutrophication-driven deoxygenation. Then, the actions required to address adaptation to restore and protect marine organisms and fisheries are by securing marine protected areas and catch-free zone in well-oxygenated regions that can serve as refugia to protect populations when the oxygen level is low as compared to the moderate level, and minimise fishing pressure on hypoxia-intolerant aquatic species by fully utilise fishing gear that lessens additional stress on oxygen-impacted marine life. Next, the actions needed to address the implementation and maintain monitoring and analysis program is by implementing continuous DO monitoring, data analysis, and dissemination of results. These are critical to detect problems and determine the effectiveness of management and restoration efforts.

The detection of oxygen solubility is of great importance. For the presence and application of oxygen gas, more studies have been made on the development of excellent precision, robustness, performance, sensitivity, reliability, with low potential toxicity and processing cost of the DO sensing devices to make a profound impact on water security as part of the Sustainable Goal Development initiative. Again, DO is one of the essential parameters in accessing water quality and necessary to be kept at a sufficient level for the survival of many forms of aquatic biodiversity. This paper mainly introduces the progress of optical glass micro-fibre transducers for DO sensing and monitoring.

2. Water security
Safe and readily water with a moderate amount of DO is essential for life. In absolute terms, water is not in short supply throughout the planet. The majority of the earth’s surface is composed of water, 97% of this water constituted of saltwater, the clean/freshwater used to sustain human is only 3% of the total amount of water on earth. In other words, only less than 3% of the world’s water can drink, of which 2.5% exists in the frozen phase in Antarctica, the Arctic, and glaciers. However, our humanity must, therefore, rely on 0.5% for all ecosystems and freshwater needs. Addition to this, according to the United Nation Organization (UN-Water), unfortunately, the total usable clean/freshwater supply for humans and ecosystems is only about 200, 000 km$^3$ of water with less than 1% of all freshwater resources, showing that we are consuming water on an unprecedented scale. Until today, it is estimated that water use has been growing at more than twice the rate of the human population increase. Water consumptions are predicted to increase by 50% by the year 2025 in developing countries, including Malaysia, and another 18% in developed countries [23]. This severe issue of lacking access to a moderate amount of DO in freshwater, followed by two-thirds of the world's human population could be under stress conditions. At least 1.8 billion people will be living in regions with contaminated water with faeces can transmit diseases such as sanitation-related diarrhoeal to cause more than a half-million diarrhoeal deaths each year. By 2050, MIT researchers found that more than half of the world's population would live in water-stressed areas, and another billion might lack sufficient water as a result of increased economic development and climate change. [24]. Moreover, the world’s growing human population makes this even more pressing. In other words, we will reach a global human population of 10 billion by the end of the century, which is unprecedented in human history. Water security is one of the significant concerns included in our National Priority Areas to create better management of water resources in Malaysia. Water security was defined as reliable access to adequate quantities of clean / freshwater to maintain adequate standards of livelihoods, proper sanitation, and sustainable health care, and the most important is for agriculture and aquaculture activities coupled with an acceptable level of water-related risks. It can be achieved when there is enough freshwater for everyone in a region, and the freshwater supply is not at risk of disappearing. Water scarcity is the most powerful threat to water scarcity. Besides, water quality can be compromised by the presence of contamination such as infectious agents, toxic chemicals, bio- and radiological hazards, and many more that can harm humans. It is, therefore, significant for action by all countries; poor-, middle- and rich-income, to promote prosperity while protecting the planet to increase the amount of safe/clean water resources. There are 17 strategic planning [25] to transform our world for a better world, as set by 2030 Sustainable Development Goals. There are two strategic planning associated with our study that is to have proper access to clean water and sanitation [26], and to ensure sustainable consumption and production patterns of safe/clean water.
[27], in order to develop new securities technologies to detect and monitor water contaminants and prevent security breaches. On top of that, on previous March 22nd, 2019 was reserved for a great event of ‘World Water Day 2019’ with the theme of ‘Living no one behind’ as part of reflection and adaptation of the central promise of the 2030 Agenda for Sustainable Development: as sustainable development progresses, everyone must benefit [28]. Therefore, for this motivation, DO monitoring in water is vitally important to many other aspects as well.

3. Global industry analysis: a perspective on size, share, growth, trends, and forecast
In the early stage of optical fibre development in the 1980s, a market scenario for the optical fibre for sensing is in its infancy, lagging behind the optical fibre for communication market size by from 5 to 10 years, through the future looks healthy. According to a survey by Gnostic Concepts, the optical fibre for sensing is likely to expand through the 1980s at a rate of 30% annually to a market size of 50 million to 100 million U.S. dollars by 1990. A survey done by the Kessler Marketing Intelligence is even more optimistic, citing a market of 180 million U.S. dollars by 1991, dominated by industrial sensor applications. A more recent survey conducted by the Market Research Future, the market sensing optical fiber is expected to grow at a rate of more than 11% between 2016 and 2022, to a market size that may hit up to 3 billion U.S. dollar opportunity by 2022. The growing deployment of the optical fibre for sensing in most common ecosystems, such as agriculture and aquaculture, are the major growth drivers of the optical fibre sensor market during the forecast period from 2016 to 2022. Several countries such as U.S., Canada, and Mexico under the North America continent are predicted to dominate the optical fibre for sensing of the global market during the forecast period from 2016 to 2022 followed by Europe focusing on increasing their production and demand, improving distribution network to boost the region’s market growth. These are the examples of major players in optical fibre for sensing include ABB Ltd. (Switzerland), Yokogawa Electric Corporation (Japan), OmniSens S.A. (Switzerland), Deltex Medical Group PLC (UK), Finisar Corporation (U.S.), AP Sensing GmbH (Germany), Sumitomo Electric Industries Ltd. (Japan), AFL Group (U.S.), Luna Innovations Incorporated (U.S.), and others. However, none of these owned by the Malaysia entity due to lack of awareness from the public, policies and limited support from the government, and knowledge transfer between a research institution and industry.

4. Typical methods to characterise dissolved oxygen level and treatment of gas supersaturation
Under the ambient temperature and pressure, the magnitude of total DO pressure in water is the same as the atmospheric pressure using the barometric technique. The differential pressure or change in pressure or sometimes preferred over percent supersaturation between local barometric pressure and total gas pressure, indicated by the symbol of ΔP, measured directly with the conventional membrane diffusion instrument [7, 29]. If the differential pressure indicator shows less than zero, bubbles do not form in the water, regardless of the magnitude of the supersaturation of an individual gas. Theoretically, the general formula in determining gas supersaturation is described as in Equation 2, where TGP, BP, and AP is total gas pressure with the unit in %, barometric pressure, and atmospheric pressure, respectively, proposed by Dawson in 1986 [30].

\[
TGP \% = \frac{BP + AP}{BP} \times 100
\]  

(2)

Until today, several precise measurements of the solubilities of gases in distilled water and seawater by various researchers have shown excellent agreement; however, there has been little agreement on methods of smoothing and representing their results. A conventional instrument such as a gaseous saturation-meter was used to analyse and self-free monitoring the water supply for possible gas supersaturation. Direct measurement of the total gas pressure with membrane-diffusion instrument so-called ‘Weiss saturometer’ such as those described by Buock from United States Fish and Wildlife Service in 1982 [31], and Fickeisen and research team from Battelle Northwest Ecosystems Department in 1975 [32], inspired from methods of Weiss. In both studies, they concluded routine monitoring of the
solubility of the gasses should be done at least every 7 days, to detect gas supersaturation or gas bubbles that might develop from air leak in shaft seals and suction pipes. As compared to the general formula in determining gas supersaturation as proposed by Dawson [30], the following formula is required for computation of total percent gas supersaturation \( S_{\text{tot}} \) from barometric pressure \( P_{\text{atm}} \), saturometer gauge pressure \( P_{\text{sat}} \), and water-vapour pressure at the ambient temperature \( P_{\text{H2O}} \) with the unit of mmHg is described as in Equation 3.

\[
S_{\text{tot}} = \frac{P_{\text{atm}} + P_{\text{sat}} - P_{\text{H2O}}}{P_{\text{atm}}} \times 100
\]  

(3)

A pioneering computational study using the methods of Weiss [33] focusing on the measurement of solubilities of oxygen and also other types of gasses such as argon and nitrogen was conducted. The precise data on total gas pressure, barometric pressure, and temperature (from 0 to 40°C) were adopted to compute percentage saturation or solubility of total gasses in distilled and seawater. The solubilities of each gas in units of the Bunsen coefficient, ml/l, and ml/kg are fitted to thermodynamically compatible equations using the least-squares method as a function of temperature at constant salinity. Theoretically, solubilities have been reported in terms of the Bunsen solubility coefficient \( \beta \), air solubility \( C^* \) with the unit of ml/l, or Henry’s constant law \( K \). The air solubility is defined as the volume of gas at standard temperature and pressure (STP) absorbed from the water-saturated air at a total pressure of 1 atm, per unit volume of the water at the measured temperature. When the partial gas pressure is 1 atm, the Bunsen coefficient is defined as the volume of gas absorbed at STP at the temperature measured per unit volume of liquid. As a result, the analysis of oxygen and other gasses solubilities in seawater and distilled water was exceptionally well provided with reasonable precision solutions. The estimated solubility accuracy under the laboratory conditions of oxygen was found \( \pm 7 \times 10^{-5} \) in \( \beta \) or \( \pm 0.015 \) ml/l or ml/kg in \( C^* \), nitrogen was found \( \pm 6 \times 10^{-5} \) in \( \beta \) or \( \pm 0.05 \) ml/l or ml/kg in \( C^* \), and argon was found \( \pm 1 \times 10^{-4} \) in \( \beta \) or 0.0009 ml/l or ml/kg in \( C^* \), in distilled and seawater.

There were several attempts to treat gas supersaturation in water. In the earliest findings for the gas supersaturation problems is the use of hatchery aerators that passed water over an inverted cone in order to increase water surface area and decrease gas pressure [4]. Thus, there is a vast improvement where the procedures have reduced gas saturation from 140% to about 104%. In other findings observed in 1953, the passage of water over a series of three weirs reported has reduced the percentage of solubility of the gas to 110%. In the separated study, the percentage of gas solubility has reduced to 102% with the used of a splash tower supported with a series of baffles. None of these three approaches mentioned above effectively eliminated supersaturated gas within the water. However, by doing so, most of the gas species have been reduced to a tolerated level. Other studies suggested that there were more sophisticated devices such as a mechanical degassing system able to alleviate the saturation level of gaseous to 100% or less than that in hatchery water [34]. A similar approach of vacuum degassing concept was utilised to reduce gas saturation levels from 133% to less than 100% [35], where the application of a slight vacuum to a packed column may cause a reduction in pressure to release dissolved gases to the surface of the water. A few years later, Dawson and the research team [36] also proposed an integrated degassing system with pack-column to decrease gas saturation levels. In their approach, the saturation level of the gaseous had reduced from 133% to 105% when the water was passed through packed columns. The flowing water was then subjected to vacuum pressure, and therefore, a great achievement was observed when the degasser is further reduced the oxygen saturation levels down to 86%. After compiling the previous work done by prominent researchers, in our point of view, daily or continuous monitoring may be desirable. The treatment device should be triggered automatically whenever the preselected or tolerated the level of gas supersaturation occurs.
5. Typical design of optical glass micro-fibre based transducers for dissolved oxygen sensing and monitoring

Until today, several designs of DO sensing device based fluorescence quenching have been reported. In the year 2011, a haemoglobin-based highly sensitive DO sensing device has been proposed [37]; using surface plasmon of a common path homodyne interferometry detector, where the oxygen solubility was obtained by quantifying the phase shift associated with surface plasmon. The detection limit of this DO sensing device was observed as low as 10 ppm, with the reaction time was less than 0.42 seconds at ambient temperature.

In 2013, palladium (II) complexes were utilised in a similar design of the DO sensing device to demonstrate this luminescent material was useful in quenching oxygen [38]. They found that the proposed DO sensing device had excellent stability, high sensitivity, and quick response time. In another study done in the same year, palladium (II) doped in complex composite xerogel in the design of DO sensing device was proposed [39]. The sensitivity of the proposed design was about $I_{O_2}/I_{N_2} = 263$, where $I_{N_2}$ was the fluorescence intensity in an anaerobic state, and $I_{O_2}$ was the fluorescence intensity in an all-oxygen state) and linearity of the oxygen concentration level was observed to be in the range of 0 to 100%. Interestingly, the proposed sensing device was observed to achieve a good response time. The response time was only in 2 s when the detection environment switched from pure nitrogen to pure oxygen, and when the environment switched from pure oxygen to pure nitrogen, The response time was more than 30 s delay.

In the following study done in 2013, an integrated microvolume optical fibre based sensor was developed [40]. The sensing region was fabricated by the dip-coating technique with a layer of hybrid fluorinated organically modified silicate film complex. The sensitivity of the DO sensing device was observed to be 13 supported with the limiting oxygen detection of 0.009%, and the response time was about only 1 s. In short, the proposed DO sensing device could be used for breath-to-breath oxygen level determination due to its low fabrication cost, ease of manufacture, quick response, less hydrophilicity of sensing luminescent material, negligible temperature variation, and appropriate sensitivity.

The contribution of the dangling bond in the complex supramolecular membrane may influence the performance of the DO sensing devices. In 2016, the fabricated DO sensing device exhibit a proportional response to oxygen level due to the existence of dangling bond [41] in this luminescent material exhibited both phosphorescence and fluorescence dual emission at ambient temperature. Besides, this design of the DO sensing device had strictly linear Stern – Volmer characteristics with reversibility, stability, and quick response and recovery time within the oxygen concentration of 0 to 100 %.

In order to relate to our research of interest, gas supersaturation problem is often first detected when the signs of distress in fish become worst due to gas bubble disease are seen. These signs appear too late. Then, massive mortality commonly, death may occur before proper preventions, and equipment needs to be installed to alleviate the health complication in fish. The world is currently facing a gas bubble disease problem. Optical glass micro-fibre based transducers might still provide a solution. In future work, low-cost, high efficiency of DO sensing devices associated with the advancement of the internet of things implementation; able to operate continuously without human attention. The proposed sensing devices can trigger an alarm system and thus protect aquatic lives from hyperbaric-supersaturation or hypobaric gas pressures, usually due from high to low DO levels with good response and recovery time.

6. Mechanism of light modulation characteristic in the optical glass micro-fibre based transducers

The optical sensing method of DO monitoring mainly based on the principle of the annihilation of luminescent materials. The luminescence DO sensing devices based on the principle of fluorescence quenching is reviewed. The detection principle of oxygen concentration or solubility for optical glass micro-fibre based transducers is that some exciting fluorescent molecules coated on optical glass micro-fibre undergo quenching through collisional interaction with oxygen molecules within the water.
Electrons are excited from the ground to the excited state (absorption) to obtain a certain amount of energy if some fluorescent molecules are treated with a specific wavelength of light. At the current stage, electrons in the excited state are unstable. Therefore, vibrational relaxation occurs through the phenomenon of channelling between systems. When the oxygen molecules collide with fluorescent molecules, oxygen molecules release the energy of the fluorescent molecules, and fluorescent molecules rapidly return to the ground state, to prevent the immediate production of fluorescence. For quantitative monitoring of dissolved oxygen in water, the following formula is required. It is necessary to establish a relationship between the measured optical parameters and oxygen concentration by a calibration procedure. According to the Stern-Volmer relationship written in Equation 4, where $I_0$ and $I$ are the fluorescence intensities under hypoxia (ref. value), and at different oxygen concentrations; $\tau_0$ and $\tau$ are the fluorescence lifetime under hypoxia (ref. value) and at different oxygen concentrations; $K_{SV}$ is the time Stern–Volmer quenching constant; and $[O_2]$ is the oxygen concentration at the time of measurement. In order to have an excellent performance of DO sensing devices, fluorescence intensity, and oxygen concentration are expected to have a linear relationship.

$$\frac{I}{I_0} = \frac{\tau}{\tau_0} = 1 + K_{SV}[O_2]$$

The principle of fluorescence quenching has few interferences and high measurement accuracy. This approach has excellent repeatability and stability and provides long-term in-situ measurements. However, the major hurdle by using this approach is all of the materials (i.e., nanometre-thick film) coated on the tapered region of optical glass micro-fibre based transducers are using rare metal complexes, resulting in high fabrication or manufacturing cost. Besides, the nanometre-thick film-coated at the tapered region may be sensitive to heat, which is the change in temperature in water that affect the efficiency of the fluorescence quenching. Therefore, it is necessary to compensate for temperature variations before the DO level measurement starts.

7. Conclusion

Progress in the design of DO sensing devices has been reviewed, and the outlook for the future direction of these devices development is highlighted. Every type of DO sensing device has achieved many exciting developments. The performance of each DO sensing device has been compared, including its advantages and disadvantages. However, some limitations in sensing and its mechanistic processes still hinder their development and also critical research directions. In conclusion, the debate on this issue continues.

Acknowledgement

This work is financially supported in part by the Malaysia Ministry of Education (MOE) under the Fundamental Research Grant Scheme with a cost centre number of 5F191, and in part by the Research Management Centre (RMC) under grant scheme of UTM GUP with a cost centre number of 13J79. MSS acknowledges the partial funding from the UTM Zamalah Scholarship Award provided by the School of Graduate Studies, UTM. Support from the People's Trust Council under the Ministry of Rural Development is greatly acknowledged. We want to thank the critics of the anonymous reviewers and valuable suggestions for improving this article.

Competing interests

The researchers have identified no possible conflict of interest.

Authors’ contributions

The authors provided the same contributions to this manuscript. The authors approved the final manuscript.
References

[1] Giomi F, Barausse A, Duarte C M, Booth J, Agusti S, Saderne V, Anton A, Daffonchio D and Fusi M 2019 Sci. Adv. 5 eaax1814
[2] Renno W C 1963 Trans. Am. Fish. Soc. 92 320-22
[3] Marsh M C and Gorham F P 1904 Report of the Bureau of Fisheries / United States Department of Commerce and Labor, Bureau of Fisheries 343-76
[4] Harvey H H 1975 Chemistry and Physics of Aqueous Gas Solutions 450-85
[5] Harvey H H 1967 Trans. Am. Fish. Soc. 96 194-201
[6] Ou Y, Li R, Tuo Y, Niu J, Feng J and Pu X 2016 Ecol. Eng. 95 245-51
[7] Colt J 1986 Aquacult. Eng. 5 49-85
[8] Hutchinson G E 1957 Limnol. Oceanogr. 1 108-14
[9] Crunkilton R L, Czarnezki J M and Trial L 1980 Trans. Am. Fish. Soc. 109 725-33
[10] Nebeker A V, Hauck A K and Baker F D 1979 Water Res. 13 299-303
[11] Chamberlain G W, Neill W H, Romanowsky P A and Strawn K 1980 Trans. Am. Fish. Soc. 109 737-50
[12] Riemann B et al. 2016 Estuar. Coast. 39 82-97
[13] Breitburg D et al. 2018 Sci. 359 eaam7240
[14] Earle S E, Wright D J, Lefroy D, Baxter J, Safina C and Elkus R 2018 Sci. 359 1475-76
[15] Stern N 2007 The Economics of Climate Change: The Stern Review (Cambridge: Cambridge Univ. Press) pp 1-662
[16] Whitney F A, Freeland H J and Robert M 2007 Prog. Oceanogr. 75 179-99
[17] Stendardo L and Gruber N 2012 J. Geophys. Res. 112 C11004
[18] Stramma L, Johnson G C, Sprintall J and Mohrholz V 2008 Sci. 320 655-58
[19] Rabalais N N, Cai W J, Carstensen J, Conley D J, Fry B, Hu X, Quiñones-Rivera Z, Rosenberg R, Slomp C P, Turner R E et al. 2014 Oceanogr. 27 172-83
[20] Diaz R J and Rosenberg R 2008 Sci. 321 926-29
[21] Breitburg D 2002 Estuar. Coast. 25 767-81
[22] Levin L A 2003 Oceangr. Mar. Biol.: An Annu. Rev. 41 1-45
[23] Barbier E 2015 Handbook of Water Economics (Cheltenham, UK and Northampton, MA, USA, Edward Elgar Publishing) p 550
[24] Roberts A G, Predicting the future global water stress, MIT News. http://news.mit.edu/2014/predicting-the-future-of-global-waterstress
[25] https://www.un.org/sustainabledevelopment
[26] https://www.un.org/sustainabledevelopment/water-and-sanitation/
[27] https://www.un.org/sustainabledevelopment/sustainable-consumption-production/
[28] http://www.worldwaterday.org/theme/
[29] Colt J 1984 Am. Fish. Soc. 14 154
[30] Dawson V K 1986 Progress. Fish-Cult. 48 142-46
[31] Buock G R 1982 Trans. Am. Fish. Soc. 111 505-16
[32] Fickkeisen D H, Schneider M J and Montgomery J C 1975 Trans. Am. Fish. Soc. 104 816-20
[33] Weiss R F 1970 Deep-Sea Res. Oceanogr. Abstr. 17 721-35
[34] Fuss J T 1986 Progress. Fish-Cult. 48 215-21
[35] Marking L L, Dawson V K and Crowther J R 1983 Progress. Fish-Cult. 45 81-3
[36] Dawson V K and Marking L L 1986 Progress. Fish-Cult. 48 281-84
[37] Choi H D, Park Y, Cho K, Rhee B K and Hong J M 2011 Opt. Commun. 284 4588-91
[38] Chu C S and Chuang C Y 2014 J. Lumin. 154 475-78
[39] Chu C S 2013 J. Lumin. 135 5-9
[40] Xiong Y, Ye Z, Xu J, Zhu Y, Chen C and Guan Y 2013 Anlst. 138 1819-27
[41] Zeng H, Zhang C, Huang Y and Lu Z (2016) Chin. J. Chem. 34 873-77