WHITE PAPER

How the latest advances in dissolved oxygen sensor technology are delivering enhanced levels of accuracy and reliability

How optical sensors can optimize dissolved oxygen measurement accuracy in aeration processes. Measurement made easy

Why does dissolved oxygen need to be measured?

Dissolved oxygen is a key ingredient in the efficient treatment of waste in water processes. A typical wastewater treatment plant uses four main stages of treatment – Primary, Secondary, Tertiary and Sludge.

The secondary treatment stage is the point at which organic waste is oxidized to form carbon dioxide, water and nitrogen compounds. To achieve this, most modern plants use an activated sludge system which uses a culture of bacteria and other organisms to feed on the organic materials in the sewage.

When added in combination with the right temperature, these bacteria and organisms use dissolved oxygen to burn or break down organic carbons into carbon dioxide, water and energy, clearing the water of harmful substances.

The importance of accurate dissolved oxygen control
As a key requirement for most types of life, oxygen is one of the most important parameters in water quality monitoring. As such, water operators need to keep a close eye on levels throughout the water treatment process, from the treatment of waste at the aeration stage through to the point of final discharge.

Optimizing aeration efficiency
Aeration provides the oxygen needed for bacteria to effectively treat and stabilize wastewater. Oxygen is used by aerobic bacteria in the wastewater to break down organic matter containing carbon into carbon dioxide and water.

Aeration accounts for around 66 percent of energy use in wastewater treatment processes. To put this in context, in a typical mid-sized city, 30 to 40 percent of energy use can be attributed to wastewater treatment operations. Of this, 25 percent is related to aeration.

The efficiency of the aeration process relies on dissolved oxygen levels being controlled as closely as possible. Under ideal conditions, dissolved oxygen levels should be maintained at between 1.5 to 2 ppm. If not enough dissolved oxygen is available, the aeration basins will be deprived of the oxygen needed for effective bacterial growth, negatively affecting the rate of sewage breakdown and impairing treatment process efficiency.

Too much dissolved oxygen can also have a detrimental impact. With aeration processes accounting for over half of

Figure 1 Energy burden in sewage treatment

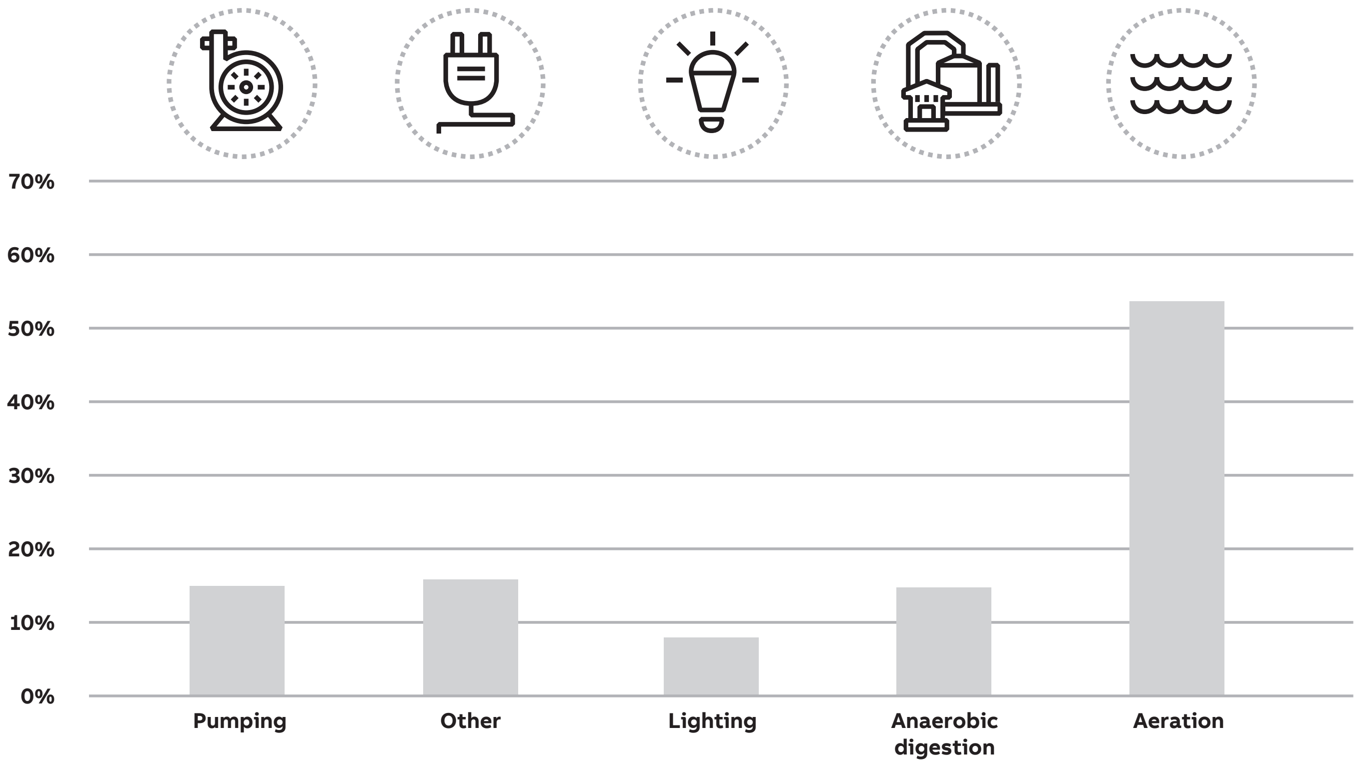


Figure 2 Optimum efficiency

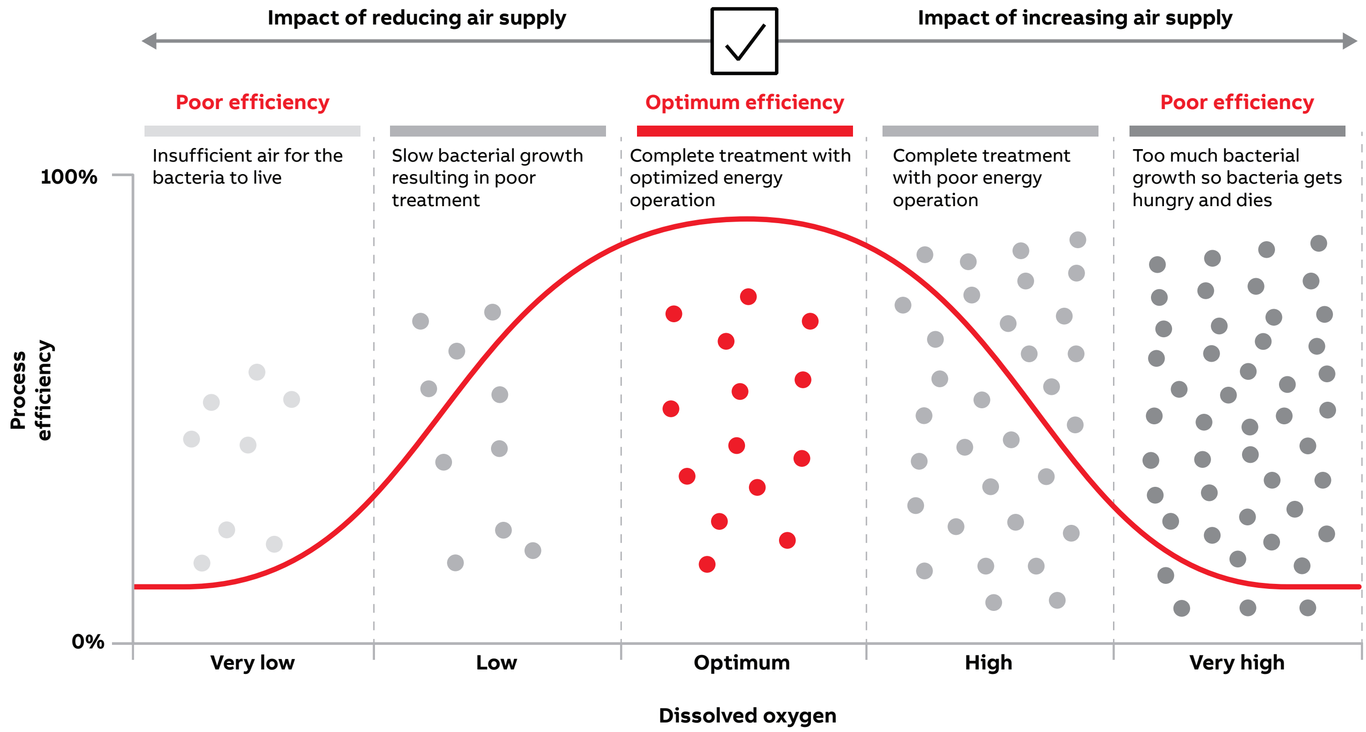
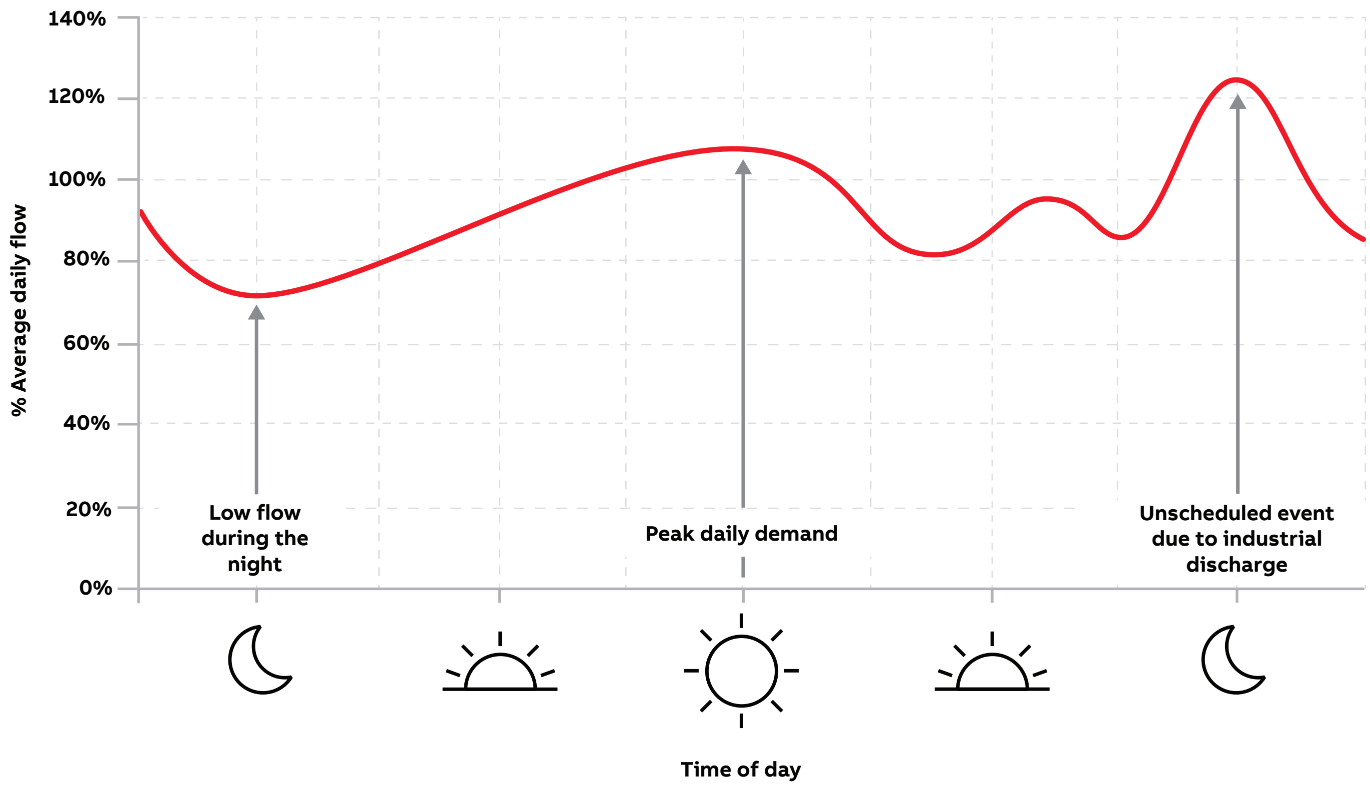


Figure 3 Average daily flow



Benefits of using ABB Variable Frequency Drives as part of a dissolved oxygen control strategy

- Drives fitted to aeration blowers provide greater flexibility of oxygen transfer to better meet demand
- Avoiding 'over aeration' can help achieve substantial annual energy savings
- Reduced mechanical stresses on the drive chain, together with reduced power consumption from precise motor acceleration and deceleration
- Combining output of ammonia and DO sensors, PLC and drives significantly reduces energy use through improved pump control

a plant's energy costs, it is vital that their efficiency is optimized as much as possible. Failing to ensure tight control of dissolved oxygen within the 1.5 to 2ppm range greatly increases the risk of operators incurring excessive energy costs.

Maximizing the effectiveness of dissolved oxygen in enabling the breakdown of organic matter depends on a variety of factors, including the characteristics of the sewage influent, the size of the basin itself and the sewage flow rate.

Minimizing environmental impact
With operators of water treatment plants facing ever stricter controls on the quality of the water they discharge, it is vitally important to ensure that anything that could affect the health of watercourses and aquatic areas.

Where dissolved oxygen is concerned, it is particularly important to ensure that levels are controlled as closely as possible. Both excessively low and excessively high levels of dissolved oxygen can be equally as harmful to aquatic life, making it essential for water treatment plants to ensure that levels are as close to ideal as possible before water is discharged.

An example is the potential creation of filamentous growths and ammonia during the wastewater treatment process caused by insufficient aeration. If left unresolved, these harmful by-products can escape into the environment, damaging aquatic life and leading to potentially stiff financial penalties for water operators.

Aeration control challenges
One of the biggest challenges for aeration control systems is variability. Treatment plant loading is subject to continuous and unpredictable changes ranging from weather, including heavy rains and fluctuations in temperature that can affect the metabolisms of microorganisms, through to the quality and quantity of influent streams can all have an impact on aeration system efficiency. Industrial 'slug loads', which may include irregular or high strength discharges, can also increase organic loads.

The consequent demands that each of these places on aeration demand can present significant challenges for optimization of both the aeration processes themselves and the equipment used within them.

To meet these challenges, systems must be able to cope with the widest range of operating conditions and be able to ensure accurate aeration control across the widest range of loads and operating conditions.

What are the main types of aeration control?
Optimum aeration efficiency in wastewater treatment processes is typically achieved using one of two main methods – surface aeration and diffused or blower aeration.

Surface aeration
In this method, water is pushed up from under the surface into the air. The resulting action of the droplets falling back down creates the ideal conditions for oxygen to mix into the water. This method is particularly effective for shallow basins or where oxygenation needs to happen quickly.

Diffused / Blower aeration
In diffused or blower aeration processes, air is introduced via a series of pipes in the bottom of the aeration basin, which then mixes into the wastewater to create the desired conditions for the aerobic digestion process to take place.

How can you maximize aeration control efficiency?
The performance of both surface and blower aeration-based processes can be greatly improved by using a dissolved

oxygen supply system that can respond quickly to changing conditions. By ensuring that the supply of air closely matches the demands of the process, substantial improvements can be achieved in aeration efficiency whilst also helping to reduce energy consumption.

In particular, innovations in variable frequency drives (VFDs), together with the latest developments in measurement and control technology – including the digitalization of a wide range of functions – are helping operators to reduce energy usage and maintain stable operating conditions under varying demands.

The improvements that can be achieved are demonstrated by comparing the classical control strategies used for blower and surface aeration with updated strategies utilizing responsive technologies that can adapt to changes in process conditions.

Traditional approaches to blower aeration, for example, have used a simple PID control loop where the air flow to the process is adjusted via a flow control valve based on the DO set point. While this maintains the DO value within the required limits, it is not able to change the speed of the blower, resulting in excessive energy consumption.

Replacing this system with one utilizing an ABB ACQ580 variable frequency drive (VFD), ADS420 dissolved oxygen sensor, SensyMaster thermal mass flowmeter and ControlMaster cascade controller will overcome these problems. Changes detected by the sensor and relayed to the ControlMaster can be used by the drive to vary the speed of the blower, reducing energy consumption and providing improved control.

In the case of surface aeration, systems commonly use a simple controller that turns a Direct On Line (DOL) starter on or off in response to readings from a dissolved oxygen sensor. Drawbacks of this method include an inability to accurately maintain the DO level within required limits, as well as the risk of damage caused by high inrush currents as the aerator equipment is turned on and off.

The solution here is to use an ABB ACQ580 VFD with an ADS420 dissolved oxygen sensing system to directly vary the speed of the aerator through accurate DO monitoring. As well as removing the need for a controller, this arrangement can also offer significant energy savings through improved performance. By reducing mechanical wear and tear from sudden starting and stopping and removing the risk of damage caused by inrush currents, maintenance can also potentially be reduced.

What are the main types of measurement techniques for dissolved oxygen?

As a key indicator of biological activity levels in water, dissolved oxygen has always been a critical measurement in wastewater treatment processes. Starting with in-situ manual collection techniques, the way in which dissolved oxygen levels have been measured has evolved as technology has become more sophisticated.

The following is a brief description of the various key methods historically used to measure dissolved oxygen.

The Winkler Titration method

Originally developed by Ludwig Winkler in 1888, the Winkler Titration method is an in-situ test involving the mixing of a known chemical alkali solution with a known acid solution to assess the level of dissolved oxygen in a sample. The process

starts with manganese sulfate being added to the water sample, followed by an alkali, iodide or azide reagent. The sample is then mixed with the presence of any dissolved oxygen being indicated by the formation of a brown-coloured precipitate (shown below as MnO2(s)). The equation for this process is shown below:

$4e^- + 4H^+ + O_2 = 2H_2O$
$2Mn^{2+} + 4OH^- = 2MnO_2(s) + 4H^+ + 4e^-$
$2Mn^{2+} + 4OH^- + O_2(aq) = 2MnO_2(s) + 2H_2O$

The sample is then mixed with a titrate of sodium thiosulfate, followed by a starch solution, to produce a blue colour. Extra titrate is then be added until the sample turns clear. At this point, the level of dissolved oxygen can be calculated, with the level being proportional to the amount of titrate added in milliliters.

Although the test is relatively simple to perform, it nevertheless suffers from several disadvantages. Firstly, the sample has to be measured as quickly as possible, in order to provide as accurate a reading as possible. Linked to this is the fact that a sample assessed using the method could only ever offer information on the level of dissolved oxygen for a specific moment of time. For wastewater treatment processes, this made any data gathered of limited value in helping to achieve a consistent level of dissolved oxygen.

Portable dissolved oxygen meters

Another common method for collecting dissolved oxygen samples is to use portable meters. Combining a handheld meter with a choice of a galvanic or optical sensor, this method offers several advantages over the Winkler test. With pre-calibrated values automatically programmed into the device, a reading can be obtained almost immediately. By eliminating the time taken to conduct a test, more measurements can be made within a given timeframe.

However, as with the Winkler test, portable meters are designed for grab samples and thus only provide an indication of dissolved oxygen levels for a particular moment in time under a particular set of conditions. This is especially important in a wastewater treatment process if the readings are used to determine the settings of the dissolved oxygen blowers. If the conditions remain consistent, then the blowers will provide the correct level of dissolved oxygen for optimum aeration. However, if the conditions are subject to variation, then additional readings will need to be taken in order for the blowers to be reset.

Online measurement

Continuously measuring dissolved oxygen levels offers the best way of ensuring that the right levels of oxygen are being delivered for maximum aeration efficiency.

When used in conjunction with modern sensing technology, an online dissolved oxygen measurement system can offer much tighter control of dissolved oxygen levels, matching them to actual oxygen demand. When coupled with automatic blower control, significant energy cost savings can potentially be realized through reduced air consumption.

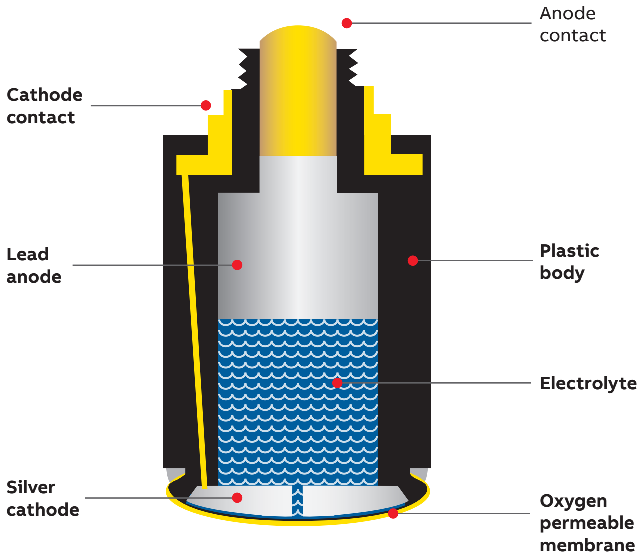
Sensor technology

There are two main types of sensors available for dissolved oxygen monitoring – electrochemical and optical.

Electrochemical sensors

Electrochemical sensors work on either the polarographic or galvanic cell principles. Both work in a similar way featuring a polarised anode and cathode with an electrolyte solution surrounded by an oxygen permeable membrane.

Figure 4 Construction of ABB's encapsulated galvanic sensor



The measurement is derived based on the difference in oxygen pressure outside and inside of the membrane. Variations in the oxygen pressure outside of the membrane affect the rate of diffusion of oxygen through the membrane itself. The cathode reduces the oxygen molecules producing an electrical signal that is relayed first to the anode and then to a transmitter, which converts the signal into a reading.

This process can be represented as:
At the anode: $2Pb \rightarrow 2Pb^{2+} + 4e^-$
At the cathode: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$
Overall reaction: $O_2 + 2Pb + 2H_2O \rightarrow 2Pb(OH)_2$ (insoluble)

The consumption of the oxygen at the cathode means that a constant flow of sample is needed in order for a reading to be as accurate as possible. In most cases, this will require the sample to be stirred constantly at the sensor tip in order to produce the necessary levels of oxygen for an accurate reading. One potential drawback of polarographic sensors occurs during start-up. In contrast to galvanic sensors where the probes can self-polarize unpowered, polarographic sensors require a 'warm-up' period, lasting from 5 to 15 minutes, for the probes to polarize. The requirement for a constant current means that the sensor consumes more power than other sensor types, making it comparatively less cost-effective.

In terms of performance, electrochemical sensors have been proven to offer similar levels of measurement accuracy to optical devices. However, their requirement for a constant flow and their susceptibility to fouling by filamentous growths such as algae, or clogging by fats oils and grease, make them comparatively less reliable under non-ideal monitoring conditions. Where this occurs, the risk of inaccurate measurement and inefficient blower control is greatly increased.

Continued sensor drift, coupled with fouling of the sensor membrane, also means that frequent maintenance, including calibration, is needed, ranging from once a month to once a day in extreme circumstances.

Optical sensors

Originally developed in the 1970s, optical sensors have evolved to overcome many of the limitations associated with their electrochemical counterparts.

In contrast with electrochemical sensors, optical sensors have no membrane or chemical components. The most advanced dissolved oxygen sensors work on the 'dynamic luminescence quenching' principle, a light-based measurement technique.

Optical sensors are comprised of lumiphore molecules embedded in a sensing element, plus blue and red LEDs and a photodiode. Figure 4 shows how an optical sensor works.

The operating principles of optical sensors are shown in Figure 5 below.

1 The sensor includes lumiphore molecules embedded in a sensing element, a blue LED, a red LED and a photodiode

2 Lumiphore molecules are excited by blue light and emit red light, which is detected by the photodiode

3 Optical electronics compute the luminescence lifetime. The luminescence lifetime is based on the phase shift between the red returned light from the excited lumiphore molecules and the red reference light from the red LED

When a reading is taken, the lumiphore molecules are excited by blue light from the blue LED. When excited, these molecules emit a red light which is detected by the photodiode. Any oxygen molecules present will quench the excited lumiphore molecules, reducing the amount of red light being emitted. The shift in the amount of red light being emitted is then measured by the red reference LED.

As DO concentration and the amount of red light being returned are proportional, a measurement can then be taken and converted into a reading based on mg/l.

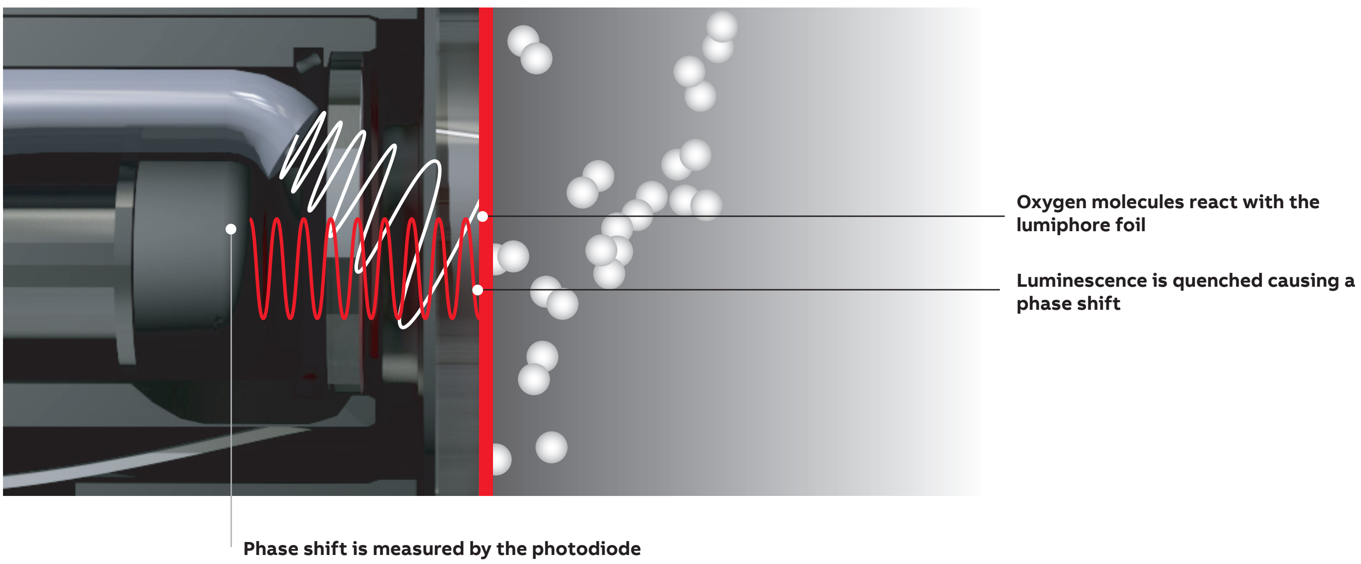
A key benefit of optical measurement technology is its stability and accuracy. The luminescence lifetime technique is used to measure the phase shift between the returned red light and the red reference light. There are two main ways of measuring the luminescence lifetime:

- **Time domain method**
  The time domain method is based on a pulsed method. Measurements are taken based on either a single or an average of a series of exponential decay events. This method measures the amount of time taken for the brightness of the light to return to a particular value.

  Inaccuracies can arise where this method is used due to drift or the presence of any stray light.

- **Frequency domain method**
  Involving the measurement and referencing of the phase shift of an entire signal against a number of cycles, this method offers much better accuracy and stability across a very wide operating range.

Figure 5 Optical sensors – how they work.



Advantages of optical sensors

Using optical sensors for dissolved oxygen measurement can help to overcome many of the problems associated with electrochemical devices. Typical benefits of optical sensors include:

- **Improved accuracy** – optical devices have been proven to deliver improved accuracy with no drift even over prolonged periods. In comparison, the accuracy of electrochemical devices can become impaired due to fouling of the membrane and / or degradation of the sensor electrolyte.

- **No need for a sample flow** – optical devices also provide an effective alternative to electrochemical sensors in low oxygen (hypoxic) conditions. Unlike membrane-based sensors, optical devices have no requirement for sample flow or stirring to artificially raise dissolved oxygen levels.

- **Low maintenance** – compared to electrochemical devices, optical sensors have a greatly reduced maintenance requirement. The sensor head only needs to be cleaned periodically, whilst the sensor cap can operate up to 2 years before replacement.

  The cost of spares is also reduced, with no need to keep spare membranes or electrolyte filling solution.

- **Long-term calibration** – the non-consumptive, non- reactive design of optical sensors means that the frequency of calibration is reduced. Optical sensor devices have been proven to provide accurate measurements for many months before calibration needs to be checked, even in applications with a higher risk of fouling.

- **Improved resistance against harsh conditions** – the sensing element in optical sensors is highly abrasion resistant, affording protection against the effects of fouling, sediment and rapid flows. Optical devices are also impervious to the effects of substances and gases such as sulphides, sulphates, hydrogen sulphide, carbon dioxide, ammonia and chloride that can affect the efficiency of electrochemical sensors.

- **Improved efficiency through smart real-time data analysis and control**
  The ADS420 can be combined with ABB's latest generation of smart digital transmitters and solutions, opening new possibilities for improved efficiency and smarter process control.

  The sensor can be used standalone or in conjunction with sensors measuring other parameters to provide a detailed overview of conditions.

  Collected data can be easily accessed in a variety of ways, through the AWT420 transmitter, via a DCS, or remotely through a secure web browser. With operators increasingly using smart devices in the field, a range of essential operational data can also be accessed whenever and wherever needed using a smartphone or tablet.

Introducing the ABB optical DO system with EZLink
Problems associated with traditional dissolved oxygen sensing systems can now be eliminated using ABB's optical dissolved oxygen sensing system.

Comprised of the ADS420 sensor and AWT420 Universal 4-wire, dual-input transmitter, the system utilizes the latest developments in optical measurement technology.

Consistent, reliable, and accurate, it can help operators to realize significant savings through reduced energy consumption and maintenance.

The ADS420 optical DO sensor uses Rugged Dissolved Oxygen (RDO)* optical technology for measuring dissolved oxygen in the most demanding process environments. Approved by the U.S. Environmental Protection Agency (EPA), this technology uses the dynamic luminescence quenching technique. Comprised of a sensor and multi-channel transmitter, it works on the frequency domain method and provides the highest levels of stability and accuracy for dissolved oxygen measurement.

The patented signal processing within the sensor enables it to respond to changes in process conditions up to five times faster than other optical systems, allowing improved process control and maximum process savings.

The sensor's robust design of the sensor enables it to withstand the problems that can affect conventional membrane-based sensors, such as abrasion, fouling or poisoning. The sensor lumiphore is not affected by photobleaching or stray light. The sensor itself is also immune to the effects of sulfides, sulfates, hydrogen sulfide, carbon dioxide, ammonia, pH, chloride and other interferences. This enables it to provide consistent, accurate readings over long periods of time without suffering from sensor drift.

The ADS420 sensor is also constructed from inert, non-corrosive materials, making it suitable for use in high salinity environments.

The use of the dynamic luminescence quenching principle means that the sensor is not susceptible to drift, removing the need for frequent maintenance.

A key benefit of the system is its simplicity. ABB's EZLink plug and play technology automatically connects the transmitter and sensor, with no need for wiring or complicated configuration. Set-up is straightforward, with a user-friendly HMI and clear menus making it easy to set parameters and view diagnostic information.

The AWT420 dual-channel transmitter provides true flexibility for measuring a wide variety of parameters in a single device. Packed with a host of features including Bluetooth connectivity, dual PID control and EZ-Link sensor connection, it helps to make water analysis easier than ever.

Operational simplicity is a key feature of the AWT420 with its powerful, yet intuitive software, advanced self-diagnostics and its modular design that enables users to achieve increased efficiency through greater user flexibility, reduced process downtime and simplified maintenance.

*RDO is a registered trademark of In-situ® Inc., Fort Collins, CO, USA

Figure 6 Comprised of a sensor and multi-channel transmitter, ABB's optical dissolved oxygen system can deliver significant savings

The AWT420 can be used with either analog or digital EZLink sensors, providing input flexibility along with benefits from digital EZLink like plug-and-play sensor connectivity.

This simplicity also extends to the sensor itself, which features a smart sensing cap with automatic setup. The SmartCap comes pre-loaded with factory calibration coefficients, serial number, lifetime indication, and manufacture date which are automatically uploaded to the sensor, eliminating the time normally required for set-up. By automatically prompting the user when replacement is due, the SmartCap also removes the risk of unexpected sensor failure.

The SmartCap is capable of up to 24 months of continuous operation, greatly reducing the requirement for maintenance. When the cap does need replacing, it will be as easy as the original installation – the calibration details will be pre- loaded and the transmitter will automatically recognize the new sensor.

When cleaning is necessary, it can be cleaned and redeployed without calibration. For high-fouling applications, the sensor can be automatically cleaned using ABB's auto-cleaning system. This system periodically injects a high pressure burst of air across the sensor surface to remove any fouling.

The AWT420 transmitter records all data to its internal memory continuously. This includes both event log/ configuration data in addition to measurement data. The transmitter's event log files contain audit log, alarm log, diagnostic log and calibration log data that is time- and date stamped, providing the operator with full audit trail capability.

The transmitter's event log files contain audit log, alarm log, diagnostic log and calibration log data that is time and date stamped, providing the operator with full audit trail capability. Various options are available for remotely accessing data held within the transmitter. An Ethernet option enables measurement readings and active diagnostics data to be accessed via a PC. Modbus* RTU RS485, Profibus DP** or HART*** communications provide the added choice of accessing data via a distributed control network.

The inclusion of an SD port also enables users to securely store data on portable devices for transfer to a PC for analysis using ABB's DataManager Pro data review software.

Applications for the ABB optical DO system

Various mounting options are also available, including dip mount systems, floating ball systems and chain mount immersion systems for open tank and channel installations, as well as a flow-through system for panel mount systems.

With a range of installation options, the ABB optical dissolved oxygen system can be used in any industry where wastewaters are rich in organic carbon and biological wastewater management is used. Typical applications include municipal and industrial water and wastewater treatment processes, aquaculture, discharge monitoring and food and beverage production processes.

Benefits at a glance

Low cost-of-ownership
- Zero drift offers stability and accuracy, with no need for calibration
- SmartCap comes fully calibrated with all the coefficients pre-programmed
- SmartCap lasts up to two years, reducing operational costs

Helps cut aeration process costs
- Enables precise control of oxygen levels, reducing energy and bacteria costs

Robust design
- Corrosion-proof design
- Resistant to abrasion, photobleaching and high salinity
- Resistant to interference from hydrogen sulphide, chloride, ammonium and others
- Chemically inert construction doesn't affect the aeration process

Simple design
- Pre-loaded factory calibrations, serial number, lifetime indication and manufacture date reduces possibility of operator errors
- The transmitter's intuitive HMI enables operators to quickly find data and adjust settings

Range of mounting options
- Dip mount
- Floating ball
- Chain mount immersion systems for open tank and channel installations
- Flow-through for panel mount systems

Fast response
- Fast response to oxygen and temperature changes, enabling close control of aeration process conditions

Ease of installation
- SmartCap pre-loaded with calibration settings
- Multi-channel transmitter features plug 'n' play approach with user friendly HMI and clear menus
- A single transmitter can connect with up to four ABB digital sensors

Flexible communications
- Multi-language
- Works with Ethernet, Modbus®*, Profibus®** and Hart*** communications
- Bluetooth**** connectivity for use with ABB's EZLink Connect app, your digital assistant in water quality measurement
- SD for data storage and graphical trending

Ease of maintenance
- Optional cleaning system for extended operation in fouling prone applications
- Long life sensor cap (24 months)
- Robust construction

Accurate results
- Uses latest technology to quantify dissolved oxygen levels
- Operates with no drift for long periods of time
- Responds quickly to oxygen and temperature changes

* Modbus is a registered trademark of Schneider Electric USA Inc.

** PROFIBUS is a registered trademark of PROFIBUS and PROFINET International (PI).

***HART® is a registered trademark of FieldComm Group

****BLUETOOTH is a trademark of BLUETOOTH SIG, INC

To find out more visit
www.abb.com/measurement

—
ABB Limited

WP/ANALYTICAL/004-EN Rev. A 05.2022