Air-blast anti-fouling cleaning for aquatic optical sensors

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Abstract: In order to solve the problem of fouling of submerged optical instruments, an air-blast cleaning mechanism was integrated into an optical sensor used for measuring suspended sediment concentration (SSC) in natural waters. Laboratory experiments in a manually created fouling environment were conducted to observe the fouling process on sensor cases made of different materials, and to verify the effectiveness of air-blast cleaning in reducing fouling. Results indicated that sensors with an aluminum case experienced more serious bio-fouling than that with polyethylene case, and the air-blast cleaning mechanism was capable of reducing fouling effect on sensor signals. So the submerged optical instruments should avoid using metal materials. The duration and frequency of air-blast cleaning can be determined and adjusted depending on actual field conditions.

Keywords: optical sensor, aquatic sensor, anti-fouling, bio-fouling, air-blast cleaning, sediment
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1 Introduction

Fouling is the accumulation of undesirable living or non-living materials on a solid surface in an aquatic environment[1]. Particularly, biofouling refers to fouling caused by accumulation of bacteria, plants, algae, or animals on submerged surfaces[2]. Solid surfaces without anti-fouling protection absorb inorganic material and macromolecules after they are submerged in water[3]. The colonization of bacteria and microbia then quickly occurs on these surfaces, resulting in a micro-fouling slime layer (a sticky coating). When the thickness of this layer is sufficient, it provides a food source to larger organisms, such as barnacles, mussels, polychaetes and various species of bryozoans and hydroids, which results in macro-fouling, the development of communities of larger and complex organisms[2,3]. Various factors, such as season in the year, sunlight, temperature, flow rates, water salinity, and water depth, have a significant impact on the degree of fouling. Winter months, less sunlight, colder temperature, higher and variable flow rate, a swing to extremely low or high salinity, and deeper water generally lead to reduced fouling[3]. Many researchers reported the extremely damaging impact of fouling on submerged optical instruments[4,5]. They believe that fouling is one of the most prevalent hindrances to long-term, continuous, in situ optical measurements because buildup of residue on the optical lens causes degradation of measurement signals over time, hence reducing measurement accuracy.

Various lens-cleaning techniques have been studied by researchers and optical sensor manufacturers. A wide variety of antifoulant coatings have been attempted[6]. However, many antifoulants are tributyltin (TBT)-based, which has a direct negative environmental impact and has been found to cause surface roughness[7].

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Flemming et al.[8] used a pulsing jet of fresh water from two small tubes to flush directly onto the glass window every half hour for 20 s to prevent fouling on sensor lenses. Suspended solids sensors manufactured by RWT[9] are equipped with a jet-cleaning system to blast air or water on a timed basis. D15/76 system, manufactured by Analytical Technology, Inc., is a turbidity monitor unit that uses a burst of compressed air to automatically clean the sensor and maintain reliable measurements[10].

Lillycrop and Howell[4] developed an optical lens protection method that fills the sampling cell with a biologically resistant reference fluid when a measurement is not taking place. The reference fluid is replaced with the water to be measured before the measurement and is brought back to the cell immediately after the measurement.

Ridd and Larcombe[11] described a simple wiper mechanism, in which a soft rubber pad is mounted upon a small wiper blade that rotates like a windshield wiper on a vehicle. Another DTS-12 turbidity sensor manufactured by FTS[12] also uses a self-cleaning wiper system. Fondriest Environmental, Inc. uses a wiper mechanism on their YSI 6136 turbidity sensor to clean residue buildup on the surface of the sensor for fouling prevention[13].

Researchers in the company of WTW[14] integrates an ultrasonic module that can generate a permanent oscillation on the optical windows in the micrometer range to avoid bio-fouling on their VisoTurb® 700 IQand ViSolid® 700 IQ sensors. The ultrasound source has maximum vibration amplitude at the center of the optical measurement window to minimize its impact on Suspended Sediment Concentration (SSC) measurements. An oceanographic sensor with in-situ cleaning and bio-fouling prevention system developed by Edgerton[15] entails the use of sonic energy which varies in frequency and energy intensity level. In the industrial cleaning processes, ultrasonic cleaning is used for a wide range of applications to remove swarf or other polishing residue from parts that are immersed in oil, grease or paint. This technique usually involves proper temperature and chemistry selection, and need relatively longer cleaning time[16].

Besides active lens cleaning techniques discussed above, proper algorithms were also used by researchers to remove fouling on sensor signals obtained from specially designed optical structures. Buttmann[17] and Postolache et al.[18] suggested that fouling of the optics on a turbidity sensor could be compensated using a four-beam technology. The four-beam sensing method includes two light sources and two light detectors. Each light source has one detector at 90° and the other one at 180° angle. Two light sources were switched on alternatively while two light detectors took readings. From the four readings, a rationmetric algorithm was used to calculate turbidity values.

During data post-processing, correction algorithms could be applied to restore the signals. For example, Zhang et al.[19] developed a correction algorithm to determine and remove the fouling trend found on a sediment sensor through a regression analysis on peak signal values taken during no-rain periods.

Taking the cost and simplicity into account, a method of air-blast cleaning to reduce fouling on optical lenses of an optical SSC sensor was investigated in this study. Different cleaning durations and intervals were used in the laboratory cleaning experiments. Fouling on SSC sensors with aluminum and polyethylene cases were studied and compared. The objective of this research was to explore a simple and efficient cleaning approach for aquatic optical sensors.

2 Materials and methods

2.1 SSC sensors

A SSC sensor has been under development and testing at Kansas State University since 2004[19,20]. The original design used an aluminum case. The tubular sensor surfaces were painted black using ultra flat paint before the experiment. The material was changed to black polyethylene for the second generation design.

The sensor uses three sets of LEDs and phototransistors that mounted on a tubular sensor surface (Figure 1). The three LEDs emit lights in the blue-green band (centered at 505 nm), orange band (centered at 610 nm), and near infrared band (centered at 880 nm); hence, they are referred to in this research as “Blue-green

LED", "Orange LED", and "Infrared LED", respectively. For the Blue-green LED, a phototransistor is mounted on the tubular surface, 90° from the LED; for the infrared LED, a phototransistor is mounted 45° from the infrared LED; and for the orange LED, two phototransistors are mounted 45° and 180° from the LED, respectively. These phototransistors are therefore referred to in this research as BG90, IR45, ORA45 and ORA180, respectively. The phototransistor mounted 180° from an LED measures light generated by the LED and transmitted through the water. The phototransistor mounted 90° from an LED measures light generated by the LED and scattered by the water. The phototransistor mounted 45° from an LED measures light generated by the LED and backscattered by the water.

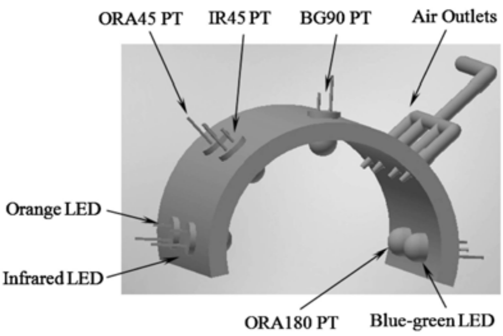


Figure 1 Tubular sensor surfaces with air outlets

2.2 Embedded air passages

For both sensor designs, air passages were embedded in sensor bodies. The air outlets were selected based on the available space in the tubular sensor surface. Four air outlets were placed about 135° from the orange and infrared LEDs (Figure 1). The SSC sensor is usually installed at the shallow waters; pressured air is introduced through the embedded air outlets to the tubular part of the sensor. Many tiny explosions on the tubular sensor surface caused by air-blast will result in powerful energy to clean the fouling materials on the LEDs and Phototransistors.

2.3 Experimental procedure

2.3.1 Aluminum sensors with 12 h cleaning intervals

An indoor experiment was conducted to study fouling on sensors with aluminum cases and to test the effectiveness of air-blast cleaning. Figure 2 shows the laboratory setup for the experiment, which consisted of two SSC sensors, a 10-Gallon fish tank, a 12 V normally closed solenoid valve (Aerocon Systems Co., San Jose, CA), a submergible air pump, a 12 V air compressor equipped with a 3.5 L air tank (Omega Research and development, Inc., Douglasville, GA), two signal conditioning and processing units, a relay circuit to drive the air compressor, a Campbell Scientific CR10X datalogger (Campbell Scientific Inc., Logan, UT), and a car battery as the power supply.

Figure 2 Laboratory setup of air-blast cleaning experiment

The fish tank was divided into two chambers with a rigid plastic sheet. Two sensors were placed side by side in one chamber of the tank and an air pump was placed in the other chamber to keep the water circulating and to maintain sediments suspended all the time during the experiment. One sensor was designed to have embedded air passages so that it could be cleaned when pressurized air blasts water into the sensor. The other sensor had no embedded air passages and it was used for comparison. The air compressor worked as a high pressure air source with a maximum output air pressure of 792 kPa (115 psi). The pressure was regulated to 413 kPa (60 psi). The CR10X datalogger was programmed to turn on a solenoid valve for two seconds every 12 hours to clean the sensor. Water in the fish tank was taken from Little Kitten Creek, Manhattan, Kansas, with a high suspended sediment concentration. The test lasted 40 d.

2.3.2 Aluminum sensors with 2 min cleaning intervals

This experiment also used water from the Little Kitten Creek with a higher cleaning frequency. Air-blast cleaning mechanism was activated for 2 s every 2 min, before taking each measurement. Air pressure of 482 kPa (70 psi) was used. Two aluminum sensors were tested. The experiment lasted 20 d.

2.3.3 Polyethylene sensors with 2 min cleaning intervals

This experiment used two polyethylene sensors. Water for the experiment was taken from Tuttle Creek Lake, Manhattan, Kansas, to intentionally create an aqueous environment rich in biological organism in order to investigate the bio-fouling effect on polyethylene sensors. For one of the sensors, air-blast cleaning mechanism was activated for 2 s every 2 min before each measurement was taken. Air pressure of 482 kPa (70 psi) was used. The other sensor was not equipped with air-blast cleaning. This experiment lasted for 17 d.

2.4 Comparison of air-blast cleaning tests between aluminum sensor and polyethylene sensor

In order to compare the differences in fouling between sensors with aluminum and polyethylene cases, and the effects of air-blast cleaning on these sensors, an 18 d experiment was conducted using two aluminum sensors and two polyethylene sensors in a small swimming pool with a capacity of 265 L (70 gallons). Water with high sediment concentration was taken from Little Kitten Creek. A submersed pump was used to circulate the water to create fouling. The sensors were placed away from the pump to avoid erosion of the fouling buildup caused by the high-speed water flow at the pump outlet. Lagoon water from the research unit of Animal Science Department of Kansas State University was added to the swimming pool to enrich a bio-fouling environment. Air-blast cleaning mechanism was activated every 12 h with a cleaning duration of 2 s.

In previous field tests, sticky fouling materials were found to adhere to aluminum sensor cases. A culturing experiment was conducted to investigate the composition of the materials. The sticky fouling materials were scraped off from the sensors and cultured in Sheep Blood Agar Plates (SBAP) under 37ºC and 25ºC, respectively. The growth medium was prepared with 50 mL/L (5%) defibrinated sheep blood, 20 g tryptone, 15 g agar and 1000 mL H_2O. After culturing for 6 days, two plates were taken out from the culturing chamber for observation and analysis.

3 Results and discussion

Two types of fouling were observed and discussed in this research: (1) bio-fouling (refers to the organic growth on the sensor's surfaces while submerged in water) and (2) clay/silt fouling (refers to the accumulation of finer soil particles on sensor's surfaces and lenses).

The water in the fish tank was taken from natural waters with a high SSC. The BG 90 signals in all experiments became very small. Therefore, the BG 90 signals were not analyzed.

3.1 Aluminum sensors with 12 h cleaning intervals

Measured sensor signals (Figure 3) clearly demonstrated signal deterioration caused by fouling and signal recovery due to air-blast cleaning. Fouling of the sensor lenses caused the transmitted signal (ORA180) to decrease and the backscattered signal (IR45 and ORA45) to increase. Steep spikes due to air-blast cleaning were clearly observed in the figure. The transmitted signal (ORA180) and backscattered signals (IR45 and ORA45) went back to their normal levels after each cleaning. The results indicated that the air-blast cleaning mechanism was capable of reducing fouling effect on sediment sensors.

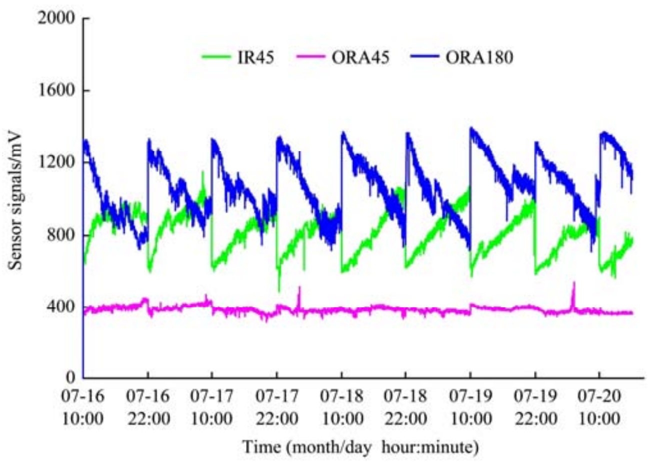


Figure 3 Signal deterioration due to fouling and recovery due to air-blast cleaning. Air-blast cleaning mechanism was activated for 2 min every 12 h

Clay/silt coating and growth of biological organisms on optical lenses are the most possible cause for deterioration of the light signals. When fouling occurred on the lenses of the LEDs, lights reaching the photo transistors at all angles would reduce. When fouling occurred on the lens of a phototransistor placed 180º from the light source, less transmitted light would be detected. On the other hand, when fouling occurred on the lens of a photo detector placed 45º from the light source, less backscattered light would be detected. However, the fact that two backscattered signals were increasing due to fouling was probably due to buildups of clay/silt or bacteria on the lens of the light source, which caused more scattered light to be detected by the phototransistor at 45º angle.

Cleaning results obtained from the aluminum sensor within a 40 d period were shown in Figure 4. Steep spikes due to air-blast cleaning were clearly observed on IR45 and ORA180 signals during the first 33 d of the experiment. Less fouling effect was observed on the ORA45 signal. Signals deterioration was accelerated after 33 d. The results indicated that the cleaning mechanism could only maintain the lenses clean for about a month, beyond which the mechanism only had a limited effect on reducing fouling.

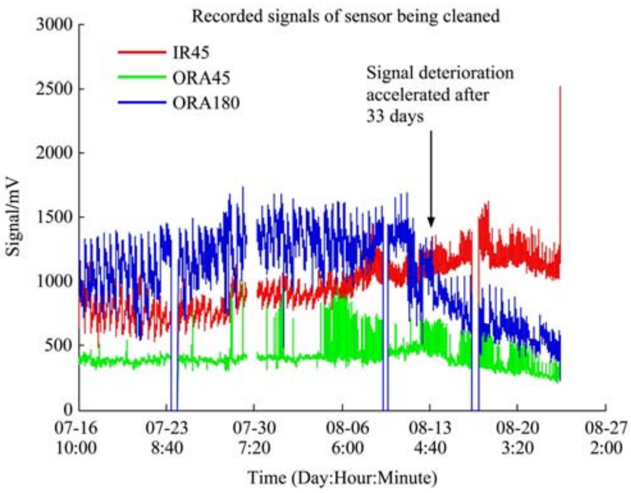


Figure 4 Signal measured from the sensor with air-blast cleaning within a 40 d period. Signals deterioration was accelerated after 33 d

However, paint around the optical component and sharp edges of drilled holes were washed off easily and the metal surfaces were then exposed to the fouling environment. Photographs indicating fouling effects on aluminum sensor case are shown in Figure 5. Photographs taken two days after the sensors were taken out from water.

Sticky materials were found to adhere to sensor cases and bare metal surfaces around optical components for both cleaned and un-cleaned sensors due to improper painting, which were hard to be removed. In the 6 d culturing experiment, a number of bacterial colonies, including Staphylococcus, Streptococcus, Enterococcus, Heterotroph, Pseudomonas and Bacillus, were observed in both plates. The growth patterns under two temperatures were identical. The culture results proved that the fouling observed on metal surfaces was bio-fouling caused by bacteria.

Figure 5 Photographs showing clay/silt fouling and bacterial fouling on sensors after a 40 d cleaning experiment

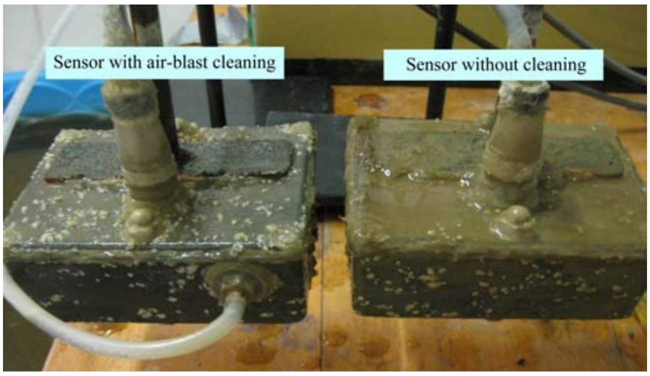
A thin clay/silt layer was only observed on the sensor case and lenses of optical components on the sensor without cleaning. It seemed that air-blast cleaning was more effective in removing the clay/silt fouling. Results also indicated that cleaning twice per day might not be sufficient under extremely dirty environment. For field deployment, the cleaning frequency and duration will need to be adjusted based on actual field conditions.

3.2 Aluminum sensors with 2 min cleaning intervals

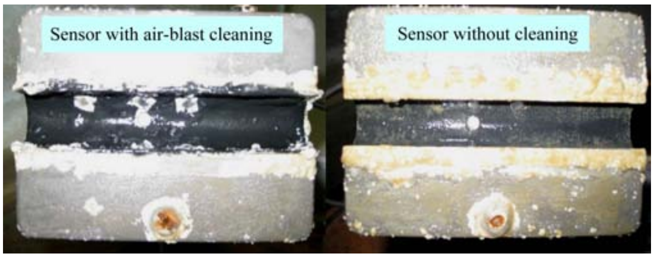
From photographs taken 20 d after the experiment started, bio-fouling spots were found on the aluminum cases of both sensors (Figure 6a). However, clay/silt fouling was only found on the sensor without the cleaning mechanism (Figure 6b). The results verified that 1) air-blast cleaning at 2 min intervals was more effective in removing clay/silt fouling than that at 12 h intervals; 2) Bio-fouling persisted even when the cleaning was activated at 2 min intervals; 3) To avoid bio-fouling, aluminum material should not be used. Manov et al.[6] suggested that copper-based materials could be employed for optical sensors for long-term submersed deployments due to its strong anti-fouling capability.

3.3 Polyethylene sensors with 2-minute cleaning intervals

Careful observation of clay/silt fouling on the sensor without air-blast cleaning (Figure 7) indicated that, clay/silt was accumulated at places where LEDs and PTs of 0º and 180º were located. This was probably because that these locations were close to the edges of the sensor case, which was not covered by the air-blast streams.



a. Bacterial fouling spots on both sensor cases

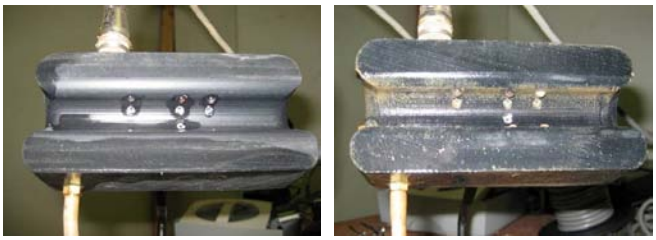


b. Clay/silt fouling only found on the tubular sensor surface without cleaning

Figure 6 Photographs showing clay/silt fouling and bacterial fouling on sensors after 20 d

Sensor with air-blast cleaning Sensor without air-blast cleaning

a. Side view



Sensor with air-blast cleaning Sensor without air-blast cleaning

b. Bottom view

Figure 7 Photographs comparing sensors with and without air-blast cleaning after a 17 d cleaning experiment was completed

3.4 Comparison of air-blast cleaning effects between aluminum sensor and polyethylene sensor

Observation of the sensors after they were operating under water for 4 d showed that air-blast cleaning was effective in removing clay/silt fouling (Figures 8 and 9). Observations of 18 d after the start of the experiment showed that both clay/silt fouling and bio-fouling persisted on both aluminum sensors, even with air-blast cleaning (Figure 10). On both polyethylene sensors, however, only clay/silt fouling was observed (Figure 11). Activating the air-blast cleaning mechanism every 12 h was not sufficient to completely eliminate clay/silt fouling, when clay/silt continuously accumulated for a long term. By observing the sensors without air-blast cleaning, a major portion of clay/silt was found at sensor edges where LEDs and PTs were located at 0º and 180º. For the sensors with air-blast cleaning, sensor edges were clean. However, there was still small amount of clay/silt found at places where PTs were located at 45º and 90º. In order to have a better cleaning result, more frequent cleaning and modification of the embedded air paths should be considered.

Figure 8 Aluminum sensors after working in water for 4 d

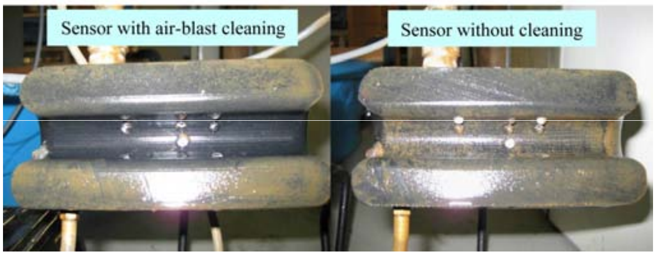


Figure 9 Polyethylene sensors after working in water for 4 d

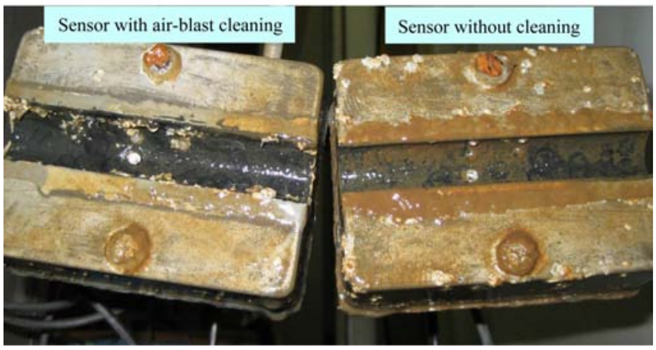


Figure 10 Aluminum sensors after working in water for 18 d

Figure 11 Polyethylene sensors after working in water for 18 d

4 Conclusions

Two types of fouling - clay/silt fouling due to clay/silt accumulation on sensor lenses and bio-fouling due to bacterial contamination - were observed on the optical sensors. Both fouling effects caused transmitted signals to decrease and backscattered signals to increase.

Clay/silt fouling and bio-fouling were both observed on sensors with aluminum case. Air-blast cleaning method was capable of reducing clay/silt fouling on aluminum cases. The tubular sensor surface of the aluminum sensor experienced severe bio-fouling even with air-blast cleaning.

Bio-fouling was not found on the polyethylene sensors. Air-blast cleaning method was capable of reducing clay/silt fouling on these sensors. Thus, for field applications, polyethylene sensors with air-blast cleaning seem to be appropriate.

The current design of embedded air paths in polyethylene sensors was not effective to clean lenses at 45º and 90º. It is, however, rather effective to lenses at 0º and 180º. Improved air path design within the sensor body, higher cleaning frequency, and longer cleaning duration would help further improve the effectiveness of the air-blast cleaning method in reducing sensor fouling.

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