A method for the growth inhibition of biofouling in Sihwa Tidal Power Plant

Seo Yeong Lee, Hee Jin Kwak, and Byung Joon Jun

Abstract—**Many facilities in contact with seawater are constantly affected by marine biofouling.**

In particular, marine biofouling cause many problems, such as reducing efficiency of water turbine, interfering with water barrier by stop log, and generating harmful gas (ammonia) due to the death of fouling organisms during Overhaul.

For this reason, Sihwa Tidal Power Plant has been researching various fouling organism reduction technologies for the past 8 years, through this, we have increased tidal power generation and operated and maintained tidal power generation facilities smoothly.

This paper presents an analysis of marine biofouling reduction technology of Sihwa Tidal Power Plant. It shows the status and characteristics of fouling organisms, problems and impacts, improvement plans and effects of the Sihwa Tidal Power Plant.

Keywords— **Commercial sodium hypochlorite injection method, Biofouling, Sihwa Tidal Power Plant**

I. INTRODUCTION

The Sihwa Tidal Power Plant, which initiated commercial power generation in 2011, is Korea's first and the world's largest tidal power plant as of 2023. Based on operation and maintenance experience and data accumulated over 13 years, this plant has become a standard model for the global tidal power generation industry.

However, given that this power plant facility uses seawater, fouling caused by marine organisms is among the main factors that affect its operation. After full-scale power production began in November 2011, a large number of marine organisms were found inhabiting each part of the aqueduct of the water turbine generator in 2012. This led to various problems, such as decreases in power generation output, difficulties during the installation of stop logs, poor drainage, and generation of ammonia gas. Therefore, countermeasures were devised for stable operation and management in the future.

This study describes the current status and characteristics of fouling organisms inhabiting the water turbine generator of the Sihwa Tidal Power Plant and its vicinity, as well as the three fouling organism reduction methods currently under study from 2012 to 2023 for application and optimal operation. Additionally, this study explored the application of commercially available sodium hypochlorite injection as an optimal fouling organism reduction technology suitable for the operating conditions of the Sihwa Tidal Power Plant, and suggests future directions based on the results of power generation output improvement and economic feasibility analysis.

Given the current lack of actual operational data and analysis of tidal power generation, we believe that this paper will help increase the field operation efficiency of tidal power generators through the establishment of a more creative and efficient fouling organism reduction technology and management strategies.

II. FOULING ORGANISMS AT THE SIHWA TIDAL POWER PLANT

A. *Habitat of fouling organisms*

The main distribution of marine organisms by structure inside the aqueduct of the Sihwa Tidal Power Plant is as follows.

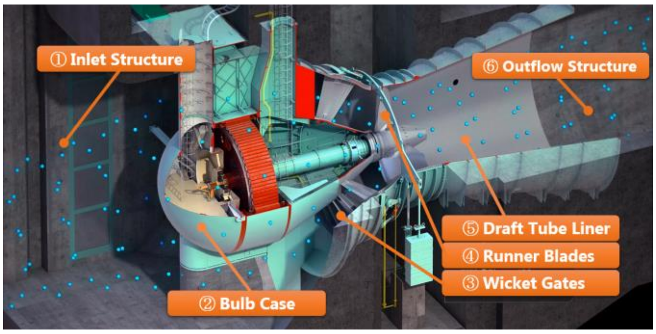

Fig. 1. Sihwa Tidal Power Plant turbine generator and structure.

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1) Sea water inlet structure

The main species in the inlet structure is the Mediterranean mussel, which forms a biofouling layer with a thickness of 200 mm to 250 mm.

Fig. 2. Drainage screen. There is a drainage screen on the wall below the seawater inlet. During a major inspection, the water in the aqueduct is drained through this drainage screen, but this is difficult due to the adhered mussels.

2) Bulb case

The main species in the bulb case is the Mediterranean mussel, which forms a biofouling layer with a thickness of 50 mm to 100 mm.

Fig. 3. Attachment of mussels to bulb case.

3) Wicket gates

The main species in the wicket gates were barnacles, which established a fouling layer that was 0.5 mm to 3 mm thick. Due to the fast flow rate in this section of the power plant, the number of individuals is generally low.

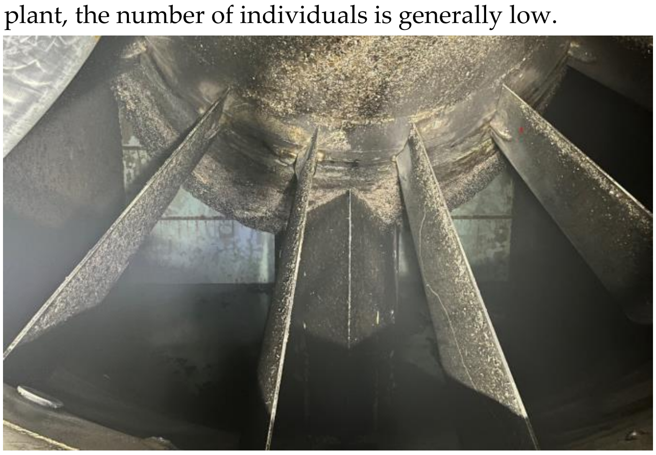

Fig. 4. Attachment of barnacles to wicket gates.

4) Runner Blades

The main species in the runner blades were barnacles, which established a fouling layer that was 0.1 mm to 1 mm thick. Due to the fast flow rate in this section of the power plant, there are few individuals.

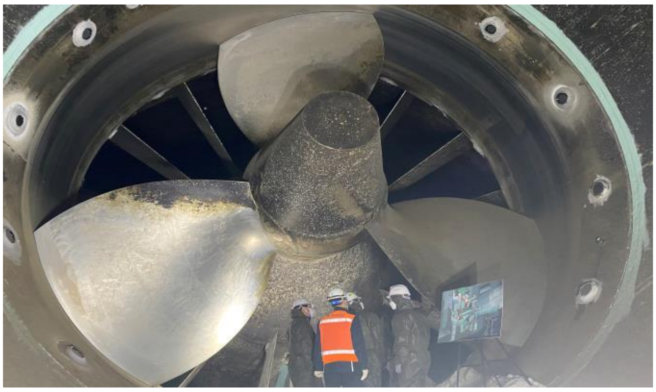

Fig. 5. Attachment of barnacles to runner blades.

5) Draft tube liner (DTL)

The main species in the draft tube liner (DTL) were barnacles, which established a fouling layer that was 2 mm to 12 mm thick.

Barnacles live in the DTL inlet where the current is fast. Mussels live at the distal end where the flow rate is slow, and the population increases progressively toward the distal end.

Fig. 6. Attachment of barnacles to draft tube liner.

6) Seawater outflow structure

The main species in the seawater outlflow structure is the Mediterranean mussel, which forms a biofouling layer with a thickness of 50 mm to 100mm.

Fig. 7. Attachment of mussels to seawater outflow structure.

Barnacles, mainly live in and around turbines with fast currents, whereas large numbers of Mediterranean mussels live around the sluice gates with slow currents. The faster the current, the smaller the size of the Mediterranean mussels.

B. Habitat characteristics of fouling organisms

Mediterranean mussels mainly cause problems by attaching to drain screens and structures at the Sihwa Tidal Power Plant. These organisms spawn from March to July and their growing season generally begins after August. In particular, mussels grow faster in warmer water but mortality rates increase if the temperature is too high. In the vicinity of the Sihwa Tidal Power Management Group, the water temperature ranges from 0.79 to 28.11 °C, which is a good condition for the growth of mussels in the summer.

Additionally, mussels are relatively weak during the spawning season. However, Mediterranean mussels cannot be easily removed due to their strong adhesion strength. Therefore, these organisms must be removed when the larvae attach and start to grow (before adulthood, August-September).

C. Problems caused by fouling organisms

Fouling organisms cause the following problems in water turbine generators, water gates, and civil structures:

- Reduction of performance by roughening the channel surface and reducing the cross-sectional area
- Decreased power generation
- Increased maintenance cost
- Poor drainage (fouling organisms block the drainage screen)
- Poor working environment due to the generation of ammonia gas during major inspections
- Damage to water stop rubber when installing a stop log
- Poor sealing when installing a stop log and water gate

Moreover, the attachment of fish and shells to the sluice roughens the surface of the passage and reduces the cross-sectional area of the passage, which decreases the performance and power generation of the affected generator.

III. TYPES OF ABATEMENT TECHNOLOGIES

To eliminate fouling, various fouling organism reduction technologies were applied to the inlet (i.e., the sea side), which particularly affects power generation outputs.

D. Natural elimination (air contact)

Natural elimination is a method of eliminating fouling organisms by emptying the water inside the aqueduct of the affected generator and circulating the air inside. In the Sihwa Tidal Power Plant, a natural elimination test of fouling organisms was conducted from 2015 to 2018 for units #1, #2, #3, #5, #8, and #9.

In the stop log, the thickness of the fouling organisms attached to the sea side (7 locations) and the lake side (15 locations) was measured, and each unit was exposed to air for more than 3 days to allow the fouling organisms to fall off naturally.

From May to August, when the temperature is low and the volume of fouling organisms rapidly increases, the longer the contact time with hot dry air, the higher the dropping rate. However, the natural dropping effect was insignificant. Additionally, the dropping effect was also insignificant when the air was allowed to circulate for 3 days, but the treatment was substantially more effective when the air was allowed to circulate for more than 6 days. Nevertheless, the cost of power generation loss increases rapidly, and therefore the economic feasibility of this strategy was very low.

Natural elimination is a method with excellent environmental safety, as it allows for the elimination of fouling organisms without the input of artificial substances. However, since power generation must be interrupted for a long time, the reduction effect is negligible compared to the power generation loss. Therefore, this approach has not been adopted at the Sihwa Tidal Power Plant after the initial experiment.

E. Application of antifouling paint

Antifouling paint is mainly used in ships and was applied to a water turbine generator. The surface becomes very smooth, which can partially reduce the adhesion of fouling organisms. However, the structures must be repainted at least every 3 years due to paint wear, which is the major drawback of this method. It also involves several days of shutdown for painting and drying, and painting near some anti-corrosion systems can interfere with the anti-corrosion system.

In 2015, Sihwa Tidal Power Co., Ltd. applied three types of silicon-based antifouling paint to one unit(#10) of a generator and tested the effect and cost.

TABLE I
COMPANY OF ANTIFOULING PAINT

Category	Company
A	Chugoku Samhwa Paints, LTD
B	BNB CO, LTD
C	Hempel

The three types of paints in the table below are eco-friendly and silicone-based antifouling paints used in marine vessels (i.e., products whose antifouling performance has been widely confirmed). These paints were pre-verified by installing monitoring specimens at water mains in 2014.

The results of the analyses demonstrated that Hempel's product performance was the best, and the power generation output increased by approximately 2.6% immediately after application.

TABLE Ⅱ
POWER GENERATION OUTPUT INCREASE RATE

Period	Power generation output increase rate
2015. 5. ~ 8.	+ 2.6%
2015. 9. ~ 2016. 8.	+ 1.1%
2018. 1 ~ 6.	+ 1.0%

However, there was a gradual decrease in power generation. Moreover, the inside of the aqueduct is highly humid, making it difficult to assess quality during painting. Moreover, the coating film tends to peel off due to constant water flow and the presence of foreign substances.

Therefore, although the application of antifouling paint can reduce the adhesion of fouling organisms and increase power generation output, this solution should ideally be implemented at the beginning of the tidal power plant construction to avoid the interruption of power generation during painting.

F. *Sodium hypochlorite injection*

Sodium hypochlorite is mainly used for the removal of biofouling in water intakes, thermal power plants, or fish farm seawater supply pipes. This compound is used to suppress the growth of fouling organisms. Injecting high concentrations of sodium hypochlorite can quickly remove and suppress most fouling organisms. However, care must be taken, as it can cause marine pollution when released into the sea.

The Sihwa Tidal Power Plant has installed seawater electrolysis facilities since 2018 to test and apply fouling organism reduction technology through sodium hypochlorite injection. The sodium hypochlorite injection method optimized for the Sihwa Tidal Power Plant was studied considering the injection method, location, duration, and concentration of the injection sodium hypochlorite.

The sodium hypochlorite application trials are summarized in the table below.

TABLE Ⅲ
SODIUM HYPOCHLORITE APPLICATION(1ST)

	Unit 3	Unit 5
Injection period	Everyday of the week (18. 6. ~ 10.)	3 days (18. 8. 21. ~ 23.)
Rate of Mortality	30%	95%
Stoplog	Open	Close
Injection location	Water level gauge 1 way	Water level gauge 1 way
Injection concentration	7000ppm (1.5 ㎥)	7000ppm (1.5 ㎥)
Injection frequency	1 time per day	2 times per day

When an injection rate of 4 ppm was maintained for approximately 3 days when the stoplog was closed, the mortality rate exceeded 95% and the removal effect was excellent.

TABLE Ⅳ
SODIUM HYPOCHLORITE APPLICATION(2ND)

	Unit 5	Unit 6
Injection period	3 days (19. 6. 14 ~ 16)	3 days (19. 9. 24. ~ 26.)
Rate of Mortality	95%	50%
Stoplog	Close	Close
Injection location	Water level gauge 2 way	Water level gauge 2way
Injection concentration	7000ppm (1.5 ㎥)	7000ppm (1.5 ㎥)
Injection frequency	2 time per day	2 times per day

Additionally, after approximately 1.5 years, the power generation output decreased gradually due to the reattachment of fouling organisms. Sodium hypochlorite injection can increase annual power generation sales by KRW 100 million(as of 2019) per unit due to the improvement in power generation output. Therefore, this method is the most feasible even when considering the initial investment.

Furthermore, in accordance with the International Maritime Organization (IMO) certified ship ballast water discharge concentration standard, residual chlorine is measured before ocean discharge and discharged to a maximum of 0.2 ppm or less. In general, residual chlorine is reduced to less than 0.1 ppm 6 hours after injection, and this concentration decreases further during actual discharge.

Collectively, the findings discussed herein validated the effectiveness of sodium hypochlorite for the suppression of fouling organisms. This approach does not require the use of seawater electrolysis facilities, which are difficult to maintain. More importantly, sodium hypochlorite injection was deemed the most effective among the three reduction technologies examined herein.

IV. COMMERCIAL SODIUM HYPOCHLORITE INJECTION METHOD

Since 2020, commercially available sodium hypochlorite at a 12% concentration has been continually injected into the affected generators. The reduction of biofouling is analyzed according to the number of days of contact with sodium hypochlorite, the location of sodium hypochlorite injection, and the concentration.

G. *Method design*

From 2020, we have been researching the effect of commercial sodium hypochlorite injection. We tested whether commercial sodium hypochlorite could produce the same effect as the experiment using the seawater electrolysis facilities.

TABLE V
COMMERCIAL SODIUM HYPOCHLORITE APPLICATION(1ST)

	Unit 7	Unit 8
Injection period	3 days (20. 7. 14. ~ 16.)	3 days (20. 9. 26. ~ 28.)
Stoplog	Close	Close
Injection location	Water level gauge 2way	Water level gauge 2 way
concentration	7000ppm (1.5 ㎥)	7000ppm (1.5 ㎥)
frequency	2 time per day	2 times per day

TABLE VI
COMMERCIAL SODIUM HYPOCHLORITE APPLICATION(2ND)

	Unit 3	Unit 5
Injection period	2 days (21. 9. 14. ~ 15.)	2 days (22. 7. 20. ~ 21.)
Stoplog	Close	Close
Injection location	Water level gauge 2 way	Water level gauge 2 way
concentration	7000ppm (1.5 ㎥)	7000ppm (1.5 ㎥)
frequency	2 time per day	2 times per day

H. Results

A linear regression analysis was conducted with the Static head as the x-axis and the Power(MW) as the y-axis. The analysis aimed to examine the changes over three time periods: 6 months after chlorination injection compared to the previous month, 7 to 12 months after injection, and 13 to 19 months after injection. The dataset used for the analysis was filtered based on the criteria of power exceeding 15.24MW(60%) and static head below 5.82m. The rate of increase was calculated within the range of static head between 3.74m and 5.82m, relative to the previous month before chlorination injection.

By dividing the data into these specific time periods and considering the defined criteria, the analysis aimed to assess the impact of sodium hypochlorite injection on the changes in power data as correlated with the Static head.

1) 1 month before injection

TABLE VII
1 MONTH BEFORE SODIUM HYPOCHLORITE INJECTION

Year	Unit	Linear regression	R^2
2020	# 7	y = 5.8811 x – 9.2014	0.9863
	# 8	y = 5.7499 x - 8.3116	0.9905
2021	# 3	y = 5.7454 x – 7.8390	0.9835
2022	# 5	y = 5.6319 x - 8.1491	0.9883

The table presents the results of the linear regression analysis conducted on water turbines unit 7, 8, 3 and 5 using the data of static head and power one month before injection. Each turbine has been analysed individually to determine the relationship between the static head and power.

2) 1 to 6 months after injection

TABLE VIII
1 TO 6 MONTHS AFTER SODIUM HYPOCHLORITE INJECTION

Year	Unit	Linear regression	R^2	Rate of power increase
2020	# 7	y = 5.5135 x – 7.0453	0.9617	2.11%
	# 8	y = 5.7509 x - 8.0689	0.9708	1.29%
2021	# 3	y = 5.6599 x – 7.2949	0.9913	0.4%
2022	# 5	y = 5.5853 x – 7.8853	0.9838	0.22%

The power increase rate from 1 month to 6 months after sodium hypochlorite injection, compared to the previous month, averaged 1.7% when injected for 3 days and 0.31% when injected for 2 days. With a 3-day injection, the power increase effect started to occur approximately 3 months after injection, while with a 2-day injection, a substantial increase in power was observed starting from around 6 months after injection. It appears that a shorter injection period results in slower detachment of fouling organisms, leading to a lower output increase effect during the first 6 months.

3) 7 to 12 months after injection

TABLE IX
7 TO 12 MONTHS AFTER SODIUM HYPOCHLORITE INJECTION

Year	Unit	Linear regression	R	Rate of power increase
2020	# 7	y = 5.8163 x - 8.2168	0.9820	4.33%
	# 8	y = 5.7077 x - 7.2872	0.9750	4.29%
2021	# 3	y = 5.6192 x – 6.4897	0.9541	3.5%
2022	# 5	y = 5.6238 x – 7.5422	0.9886	3.02%

From 7 to 12 months after injection, there was a consistently high output increase rate of 3-4%.

4) 13 to 19 months after injection

TABLE X
13 TO 19 MONTHS AFTER SODIUM HYPOCHLORITE INJECTION

Year	Unit	Linear regression	R^2	Rate of power increase
2020	# 7	y = 5.8777 x - 8.4304	0.9864	3.99%
	# 8	y = 5.6676 x – 7.5020	0.9861	2.17%

From 13 to 19 months after injection, although there were variations due to equipment failures and maintenance issues, an average power increase rate of approximately 3% was maintained compared to the previous month before injection.

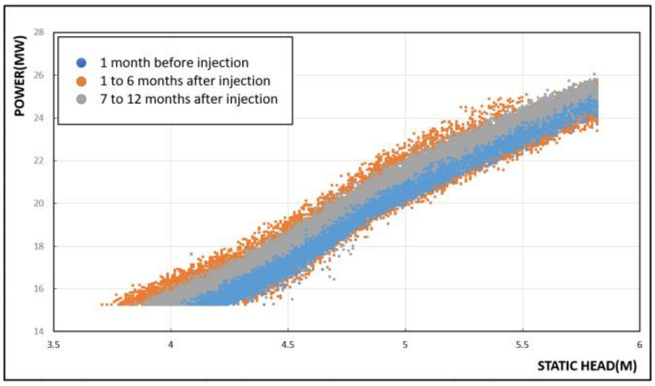

Fig. 8. Unit 7 Static head - Power scatter plot

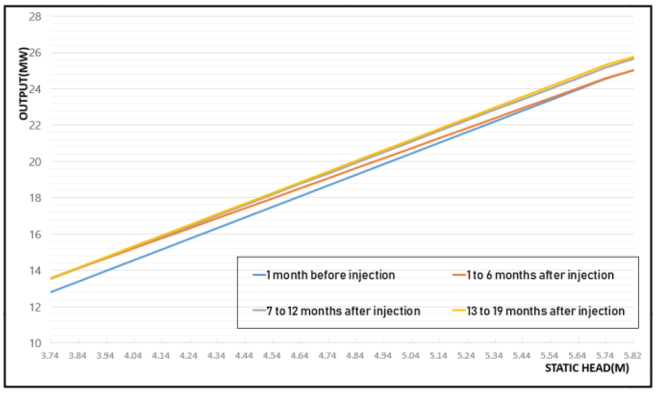

Fig. 9. Unit 7 linear regression curves

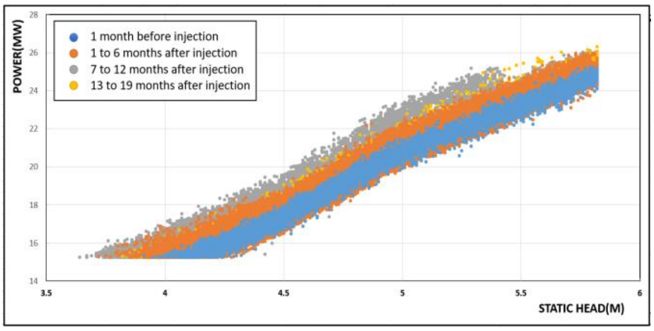

Fig. 10. Unit 8 Static head - Power scatter plot

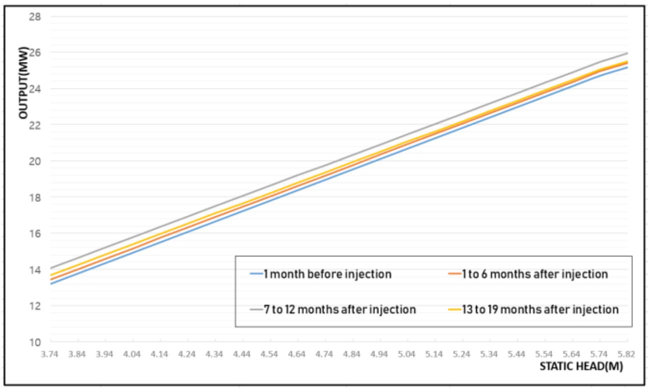

Fig. 11. Unit 8 linear regression curves

V. CONCLUSION

Considering the cost-effectiveness, fouling organism removal efficiency, and duration of effectiveness, the most suitable method for fouling reduction in the Sihwa Tidal Power Plant is the current commercially implemented seawater chlorination injection method. By closing the stop log and injecting 7000ppm of chlorine for a duration of 3 days, it is possible to achieve an approximate 3% improvement in output over a period of 1 year and 6 months. Moreover, a 3% increase in output for one unit of the tidal power generator, based on the 2022 generation performance, leads to an annual revenue increase of approximately 230 million Korean Won per unit. In the case of Sihwa Tidal Power Plant, the same method will be applied to the turbine on the lee side in 2023 to analyze the effectiveness of chlorination injection.

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