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Analysis of Particulates and SO_2 Removal from Coal Combustion Emissions Using Cyclone and Wet Scrubber With Textile Wastewater Feed

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Abstract

Reuse of wastewater in the industry is mostly accomplished for watering plants. In a closed cycle, however, industrial wastewater can be returned through treatment to save water usage. This study aims to analyze textile wastewater's ability to be used as scrubbing liquid in the SO_2 gas and particulate removal from coal combustion using a packed wet scrubber. Usually, the textile industry uses boiler fueled by coal and discharging base/alkaline wastewater. The method is carried out experimentally using a prototype device using a combination of cyclone and scrubber, with a source of coal combustion gas emissions. We did experiments using textile wastewater four times and two times using clean water as a control. We monitor the SO_2, particulate emission in the gas stream, and pH, sulfate levels, and TSS levels in collected wastewater according to SNI. SO_2 gas and particulates from coal combustion will be absorbed by the scrubber's wastewater spray so that SO_2 will dissolve into sulfate, particulate matter into TSS. The study results using textile wastewater showed the removal efficiency of particulates on cyclone by 34-78%. The removal efficiency of SO_2 on wet scrubber was only 24.7%. There was an increase in TSS levels after passing through the scrubber by 46%. The rise in TSS and sulfate concentrations in the wastewater indicates the absorption of SO_2 and particulates into wastewater. Based on this result, we can use textile wastewater for controlling the emission of SO_2 and particulate from coal combustion by feeding it for the scrubber. However, the efficiency of this process is not optimal.

Keywords: *air pollution; coal; control; emission; efficiency; industry*

1. Introduction

Coal is widely used as a fuel for industrial processes such as boilers, "power plants," and other uses. Industry in Indonesia uses coal. In addition to its relatively low price compared to other fossil fuels, Indonesia's coal reserves are quite large. Combustion coal emissions, for example, emitting a lot of hazardous trace metal elements (Nalbandian, 2012).

When the process consists of coal combustion, a significant amount of sulfur will be released, leading to air pollution and ultimately polluting water and soil. Emissions from uncontrolled coal-fired power plants indicate that sulfur oxide and PM, which enter the water, are twice as high as emissions from vehicles and factories every year. Moreover to SO_2, other SO_X, like sulfate (SO_3^{2-}), which contains fine particles, pollutes the air and water by traveling hundreds of miles from the power plant and producing sulfuric acid (H_2SO_4), a major constituent of acid rain. Dust was emitted annually to contribute to PM's formation and underlying risks to life expectancy (Munawer, 2018).

One effort to remove SO_2 and particulates is to use a wet scrubber. Pollutants that can be applied to wet scrubbers include organic vapors, vapors, gases (such as chromic acid, hydrogen sulfide, ammonia, chloride, fluoride, and SO_2), particulates, volatile organic compound, and hazardous air pollutants in the form of particulates (PMHAP). In general, wet scrubbers remove particulate through the impaction, inertia, and Brownian diffusion methods. Absorption is the process by which the dissolved component of a mixture of gases dissolves in a liquid (Richards, 2000).

On the contrary, clean water has become an environmental crisis where clean water availability is inversely proportional to community demand. Mirror to the scenario of world economic growth, global industrial consumption of water increased 1.8 times more, from 800 billion m3 in 2009 to 1,500 billion m^3 in 2015. So far, the textile industry is the largest consumer of clean

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water in the world with liquid waste, which contains various dangerous constituents if not appropriately handled (Buscio and Álvarez, 2019). Water consumption in the textile industry is 80-100 m^3 for every ton of textile product produced, and liquid waste is discharged as much as 115-175 kg COD/ton of product, coupled with organic chemicals that are difficult to measure, color and salinity (Rosi *et al.*, 2007)

Water conservation is possible by the industry in addition to its high water consumption. For example, Hansen *et al.*, 2016 reuse wastewater for cooling tower make-up water in the Petrochemical industry. The textile industry must consider water conservation for several reasons, the main one being the increasing need for clean water from various other sectors, such as the availability of clean water decreases (Shaikh, 2009). Through their research, de Aquim, Hansen, & Gutterres (2019) revealed the reuse of liquid waste. Liquid waste is one of the rational steps in preserving the environment, saving the cost of clean water consumption, and saving water treatment costs. Many advanced processes are needed for treating the textile wastewater for reuse due to the complexity of wastewater quality (Erdumlu *et al.*, 2012; Yin *et al.*, 2019). However, reused waste characteristics will determine the success of wastewater reuse in the industry (Feng, Wang, & Chen, 2006). Therefore, liquid textile waste tends to have a high pH and reasonable as a scrubbing liquid to remove acidic gaseous pollutants from coal combustion emissions.

This research objective is to analyze the potential reuse of the textile industry's alkaline wastewater to be utilized as water feeding for the scrubber process. We will analyze particulate and SO_2 removal efficiency by measuring flue gas parameters and in wastewater (from the scrubber process). Through this process, it is hoped that there will be added value in saving water use due to using wastewater instead of clean water. It is also expected that the scrubber process for acidic gases neutralizing by alkaline textile wastewater can be optimized.

2. Research Methods

The study was conducted with a laboratory-scale experimental method described in the schematic of the research device (Figure 1) or in the actual experimental prototype (Figure2) from A (furnace), C (cyclone), F (scrubber) sequentially as an air pollutant control instrument.

The prototype comprises of an integrated furnace with cyclone and packed column scrubber (loaded with marbles about one third). Coal combustion is performed in the furnace. Coal mass is equalized in each experiment to obtain homogeneous emissions. The scrubber flow system is countercurrent, where gas flows from below, while liquid flows from above. In this experiment, the dependent variables are combustion temperatures, emission concentration of SO_2 and particulate, concentration (in the liquid) of pH, sulfate, and TSS, while the independent variable is the L/G value. Coal mass for burning, scrubber bed height denotes for a static variable.

Then particulate and SO_2 samples are taken at three sampling points, namely, the inlet point (before cyclone), cyclone point (after the cyclone, before scrubber), and the outlet point (after scrubber). Due to

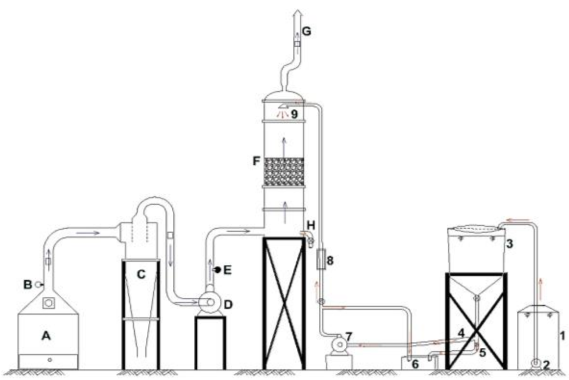

Figure 1. Experimental Diagram

Figure 2. Experimental Prototype

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device constraints, the measurement at the scrubber outlet is only for SO_2 measurements. The SO_2 emission measurements are carried out with a portable gas analyzer (Bacharach PCA3). Particulate sampling was done iso-kinetically according to SNI 7117.17-2009.

Experiments were accomplished by varying the scrubbing liquid used, namely with textile wastewater and clean water. Experiments using liquid textile waste were done four times, and clean water experiments were conducted two times. The use of pure water as scrubber feeding is only for comparison with wastewater feeding. Textile liquid wastewater was kept for 12 hours to reduce TSS levels before being used as scrubbing liquid during the experiments. Then the wastewater was pumped into the wet scrubber using a pump at 5 LPM. The cyclone flow rate was set at 240 m^3 /hour. The L/G value was measured at the scrubber outlet, and the real gas stream rate is going through the scrubber. Scrubbing samples are taken before and after passing the wet scrubber. During the experiment, scrubbing liquid samples were measured for pH, sulfate levels, and TSS levels according to the methods in SNI 06-6989.20-2004 and SNI 06-6989.3-2004.

To get the removal efficiency, the following Formula 1.

$$\eta = \frac{Q_0 c_0 - Q_1 c_1}{Q_0 c_0} = 1 - \frac{Q_1 c_1}{Q_0 c_0} \qquad (1)$$

where Q_0 is inlet flowrate (m^3/seconds), Q_1 is outlet flowrate (m^3/seconds), C_0 is inlet concentration (g/m^3) , C_1 is outlet concentration (g/m^3).

3. Result and Discussion

3.1. L/G ratio

To know the ratio of liquid to gas (L/G), we carefully measure the gas flow rate at the emission as well at the furnace outlet and compare it with the measurement of liquid flow rate at the scrubber inlet. Varying liquid flowrate is possible while varying gas flowrate is impossible due to the cyclone draft fan's static flow.

The outcome of the real L/G calculations is depicted in Table 1. The real L/G calculations results are bigger than the theoretical used L/G calculations for this research. Large L/G means having a high liquid flowrate and a tiny flow rate of gas.

Based on Table 1, the real L/G is obtained when measuring liquid and gas flowrate L/ G did not meet the EPA standards (2002) for acid gas that has around 2-20 gpm/1000 cfm. According to Richards (2000), the typical L/G ratio design for gas emission removal is higher than in particulates, which is 5-50 gallons/1000 ACF. Hence, the calculated real L/G in this research meets the typical design, according to Richards (2000).

3.2. Characteristics of Textile Wastewater

We tested the wastewater characteristics before it is being used. Based on Table 2, Textile wastewater has a high pH value as expected to remove acidic gases such as SO_2. It also had high COD, color, and TSS. These results are consistent with typical textile wastewater, namely high BOD, COD, SS, pH, and color (Yaseen and Scholz 2016). Other researchers have also identified high levels of metals (Sharma *et al.*, 2007) and temperature (Dos Santos *et al.*, 2007).

3.3. pH scrubbing liquid

Data for measuring the wastewater pH were shown in Figure 2. In tests 1 to 5, generally, the wastewater's pH decreased after being utilized as a scrubbing liquid. This shows that acidic SO_2 gas is able to lower the pH of wastewater that is alkaline even though it is not significant. In testing four and five, the pH of the wastewater has increased. Furthermore, in test 6, the pH showed somewhat stable.

Table 1. Ratio L/G during actual experiments

Testing	**Liquid Flow Rate (gpm)**	***Outlet* Volumetric Flow Rate (cfm)**	**L / 1000 cfm**
1	1,321	51,776	25,511
2	1,321	51,443	25,676
3	1,321	52,775	25,028
4	1,321	52,609	25,107
5	1,321	69,590	18,981
6	1,321	70,422	18,756
7	1,321	51,443	25,676
8	1,321	52,109	25,348

Table 2. Characteristics of Textile Wastewater

Parameter	**Unit**	**Results**	**Standard by*PERMENLH RI No.5/2014***
COD	mg / L	526.67	150
Color	pt-co	4844.3	
TSS	mg / L	1480	50
pH	-	11.87	6.0-9.0

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The difference in pH values before and after the wet scrubber is most likely rooted by the effective contact of gaseous emission with scrubbed liquid. In this study, contact of gaseous emission with scrubbed liquid is a countercurrent method. However, the liquid spray was not so small enough to make intimate contact between the gaseous pollutant and scrubbed liquid.

Theoretically, it is hard to calculate the pH of the final alkaline scrubbing solution after having contact with SO_2 gas, considering impurities in both emissions and wastewater. However, based on the study by Sharma *et al.* (2010), which stated that the pH values of NaOH solution could reach as low as 4.75 after coming into contact for 75 min with SO_2 gas from coal burning in the power plant.

3.4. Combustion Temperature

The combustion temperature somewhat influences the SO_2 emission concentration. Meanwhile, the scrubber outlet temperature indicates the contact of the liquid scrubber with gas emissions. Therefore, temperature measurements were conducted at the inlet or the furnace and the outlet or wet scrubber. The results of combustion and wet scrubber outlet temperature can be seen in Figure 3. There was a drastic temperature drop at the furnace outlet with the scrubber outlet. The temperature drop occurs along with the flow from the furnace to the scrubber. However, the largest decrease is predicted to occur between the scrubber inlet and outlet. Theoretically, the higher the gas temperature, the lower the absorption rate, and vice versa. The lower the gas temperature, the higher the absorption rate will be. High-temperature gas can also cause the solution to decrease because it evaporates. If the outlet of the gas flow temperature increase, it is an indication of a change in operation. It could be originated by increasing outlet process temperature, increasing the gas flowrate, or decreasing the liquid flowrate (EPA, 2005). With different gases, according to Abdurrakhman *et al.*, 2018, the decreasing temperature in scrubbers will increase the absorption rate of H_2S gas almost linearly. Thus, in this study, dropping the temperature significantly due to intimate contact between scrubbed liquid (wastewater) with gaseous emission from a furnace.

3.5. Analysis of Removal for Particulates on Cyclone

By installing cyclone, the performance of particulate removal in a reactor is supposed to be better. Therefore, cyclone removal efficiency needs to be identified to study its relation to the efficiency of particulate removal in wet scrubbers. The particulate removal efficiency of the cyclone is summarized in Figure 4.

In this research, a conventional cyclone is used theoretically to remove particles with sizes greater than 5 µm. Finer particles are difficult to separate through a centrifugal mechanism because centrifugal force will push the finer particle to move outside the cyclone. (Huang *et al.*, 2018; Kim *et al.*, 1990). Therefore, the cyclone's removal efficiency in this experiment removes coarse particulate matter from the flue gas, thus producing flue gas that still carries fine particulates. Figure 4 shows the fluctuating particulate removal efficiency in cyclones.

Experiment 1 - 4 depicts the cyclone eliminates particulate with varying efficiency. Experiments using wastewater as a scrubbing liquid (experiments 1 - 4) particulate removal efficiency ranged from 34 % to 78%. The highest efficiency occurred in experiment four, and the lowest particulate removal efficiency occurred in experiment one. The difference in removal efficiency was caused by mass loading entering the cyclone due to fluctuating combustion results at the furnace. In test number 6, there was an error in the combustion process, thus not shown in this graph.

Table 3 shows the amount of gas emission entering the cyclone with the cyclone's efficiency in each experiment. Experiment 4, which has the highest efficiency, also has the highest mass loading among other experiments. While in experiment 1, which had the lowest efficiency among experiments with wastewater, it had a loading mass of 1.4 m^3/minute. This is comparable to what was revealed by Huang *et al.* (2018) that a rising in loading mass will increase cyclone removal efficiency for the velocity of inlet gas less than 15 m/sec.

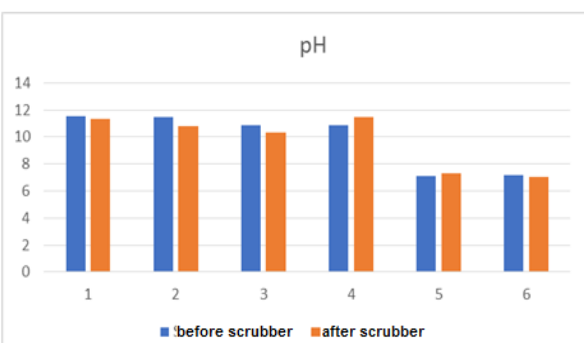

Figure 2. Liquid Scrubbing pH Before-After Scrubber

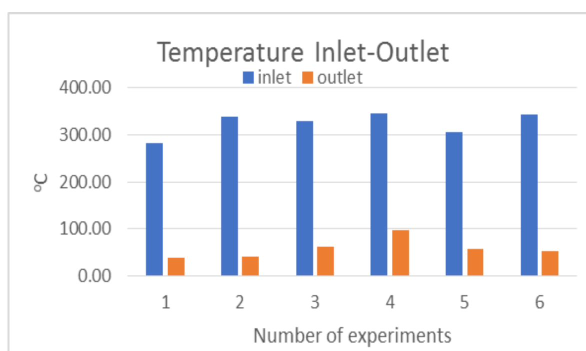

Figure 3. Scrubber Temperature Measurement Results

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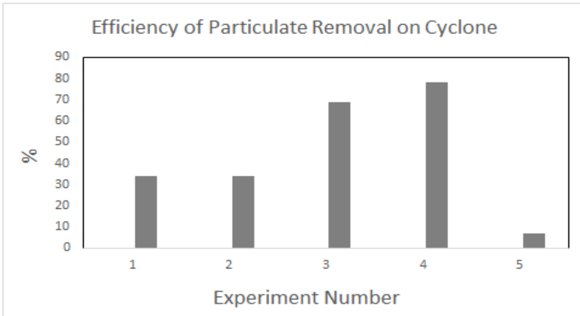

Figure 4. Graph of Particulate Removal Efficiency on Cyclone

Table 3. Mass Loading, Inlet Velocity and Cyclone Efficiency

Feeding	**Trial**	***Inlet***	**Mass**	***Cyclone***
Textile wastewater	1	3.7	1.43	34
	2	3.7	1.31	34
	3	5.2	2.62	69
	4	5.2	2.65	78
Clean water	5	5.7	1.65	7
	6	5.6	1.64	*

* error results

Besides loading mass, other parameters affecting cyclone removal efficiency are inlet velocity (Ray *et al.*, 1998). According to Byatt-Smith *et al.* (1996), the velocity of the flue gas has to be high enough to push the particle out of the path until the flue gas exits the outlet. In general, if the inlet velocity increases, so efficiency will also increase. Through their experiment, Wei, Sun, and Yang (2019) explained that the low velocity of inlet gas would cause low kinetic energy. The centrifugal force acts on relatively low particles so that it is hard to be released from its path. Suppose the inlet gas's velocity is relatively high; the radial displacement (i.e., the displacement of particles from the radial path) will be higher than the downward-directed gas velocity. In a study trial with clean water, low efficiency was obtained in experiment 5 (Table 3). The cyclone's low efficiency might be originated by improper placement of the particle measuring device after the cyclone.

3.6. SO_2 Removal Efficiency

The measurement results of SO_2 gas emission concentrations using scrubbing liquid wastewater are highlighted in Table 4, while the measurement results of SO_2 gas emission concentrations using clean water scrubbing liquid are explained in Table 5. Likewise, the emission load for particulates, emission load for SO_2 gas is also fluctuating. The experiment's efficiency by scrubbing textile waste is lower than using clean water, possibly because the contact of SO_2 gas and clean water occurs more intensively. The presence of TSS in textile wastewater makes water spray not optimal.

Based on previous research using artificial waste (Huboyo *et al.*, 2019), on average, the removal efficiency of SO_2 gas reached 36.5%. Also, compared with the same device but no cyclone installed, the removal efficiency of SO_2 is around 31-78% (Huboyo *et al.*, 2000). So this research outcome showed smaller than using artificial wastewater and no cyclone installed. As shown in Figure 6, clean water is three times better at removing SO_2 gas. The unstable gas emission input loading during the measurement causes the efficiency results to fluctuate significantly. Of course, this efficiency figure is below the expectations of the scrubber performance. Improvements to the wastewater spray system are indispensable to improve scrubber performance.

Table 4. SO_2 Removal Efficiency With Wastewater Liquid Scrubbing

Experiment Number	**SO_2 Concentration (mg/m ^{3})**		**volumetric flow rate (m^3/sec)**		**Emission load (mg/sec)**		**efficiency (%)**	**average efficiency (%)**
	inlet	**outlet**	**inlet**	**outlet**	**inlet**	**outlet**		
1	49.13	58.30	0.0291	0.0243	1.43	1.42	0.90	24.70
2	36.03	31.44	0.0293	0.0248	1.06	0.78	26.06	
3	14.41	11.14	0.0409	0.0328	0.59	0.37	38.00	
4	14.41	11.79	0.0411	0.0332	0.59	0.39	33.83	

Table 5. SO_2 Removal Efficiency With Clean Water Liquid Scrubbing

Experiment Number	**SO_2 Concentration (mg/m ^{3})**		**volumetric flow rate (m ^{3}/ sec)**		**Emission load (mg /sec)**		**efficiency (%)**	**average efficiency (%)**
	inlet	**outlet**	**inlet**	**outlet**	**inlet**	**outlet**		
5	27.08	20.09	0.0450	0.0243	1.22	0.49	59.99	60.62
6	40.18	27.95	0.0442	0.0246	1.77	0.69	61.26	

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3.7. SO_4 and TSS Concentration in Wastewater

To determine SO_2 absorption in wastewater, sulfate (SO_4) testing is performed. Sulfate testing refers to SNI 06-6989.2004 about the sulfate test method. The results of sulfate testing in wastewater are shown in Figure 7. Figure 7 shows the addition of sulfate levels of wastewater at the inlet or before use on wet scrubbers and outlets or after the wet scrubber. The addition of the sulfate content showed that the absorption of SO_2 in the wastewater. In the 5th test (not shown), sulfate levels decreased because there was no effective absorption of SO_2. A decrease in sulfate levels may be possible because fly ash attached to marbles can become absorbent and reduce levels of SO_2. According to Lee (1990), coal fly ash can act as an absorbent in SO_2 removal. SO_2 is absorbed in sulfite and sulfate form.

Figure 8 shows TSS testing results in trials with variations in liquid waste as a wet scrubber feed. Generally, the results indicated are TSS levels have increased from before to after being used as feed liquid. This increase demonstrates that the liquid feed in the wet scrubber can remove particulates from the flue gas, so the TSS levels after being used are higher than before except for the second experiment. The TSS level went up by 46% after the liquid gets through the scrubber (beyond experiment 2).

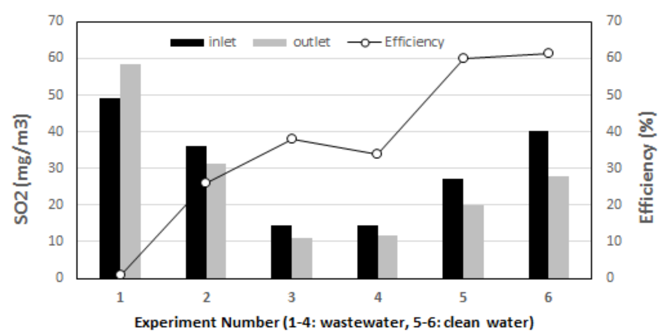

Figure 6. SO2 Concentration and Removal Efficiency

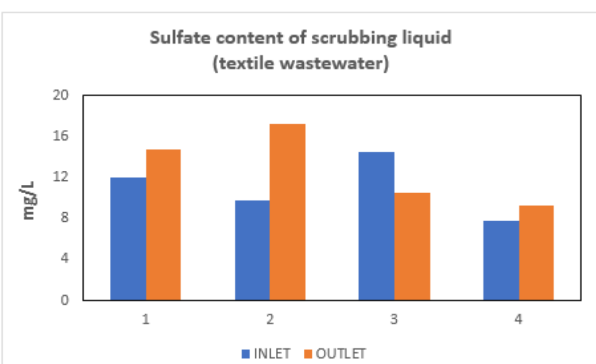

Figure 7. Sulfate Test Results in Wastewater

As showed in Figure 9, the increase of TSS concentrations during the experiment with clean water feeding showed a drastic increase with an average of 225%. Research trial with clean water, much particulate matter in flue gas is absorbed in the scrubber.

The efficiency for pollutant removal with wastewater is much lower than that of clean water. For sustainable waste treatment, industrial wastewater reuse as scrubber feed water needs to be continuously studied to achieve the desired efficiency. It is hoped that the industry will use water resources efficiently. Ultimately, water sources could be allocated for basic human needs.

4. Conclusion

The study results demonstrated that the efficiency of removing particulate matter through scrubbing wastewater feeding was on average 24.7% lower than that of clean water, which reached 60%. The increase in TSS and sulfate concentrations in the wastewater indicates the absorption of SO_2 and particulates into wastewater. Research shows the probability of using industrial wastewater to reduce water use for scrubber feeding as a feeding scrubber. Fluctuations in the mass loading rate of combustion will also produce fluctuations in combustion emissions.

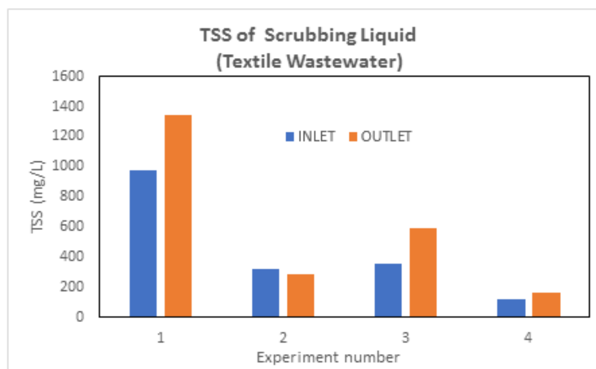

Figure 8. TSS Content of Scrubbing Liquid

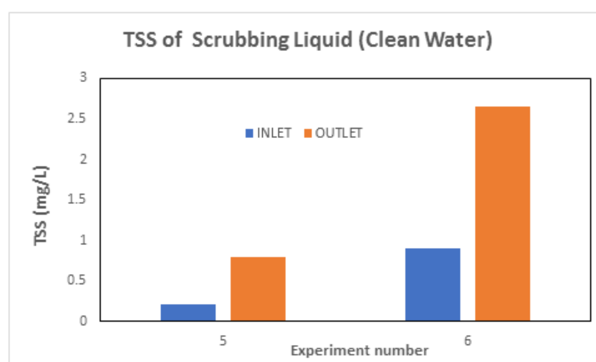

Figure 9. The concentration of TSS of Clean Water Scrubbing Liquid

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