

Influence of Coagulant Species on Sulfur Oxide (SO_x) Emission from the Textile Sewage Sludge Combustion

Ari Rahman, Naoyuki Kishimoto, and Takeo Urabe

Abstract—Simulation of textile sewage sludge combustion to investigate the typical flue gas generation was carried out by Material-oriented Little Thermodynamic (MALT) software simulation. Textile sewage sludge was modeled on the basis of loadings of effluents, daily usage of dyeing material, heavy chemical for wastewater treatment and daily production of activated sludge. Combustion temperature was set in the range of 500 °C to 1100 °C. In this research the influence of coagulant species used in wastewater treatment on flue gas especially on sulfur oxide (SO_x) generation was investigated. The replacement of conventional coagulant FeSO₄ and Al₂(SO₄)₃ to FeCl₃ gave the result of more than 18% reduction of SO_x at the combustion temperature of 850 °C and 19% at the temperature not less than 950 °C. The distribution ratio of sulfur element indicated that SO_x especially in the form of SO₂ was generated at the combustion temperature of 700 °C and the concentration increased with a rise in combustion temperature.

Index Terms—Textile sewage sludge, coagulant, sulfur oxide (SO_x), MALT.

I. INTRODUCTION

Textile sewage sludge as a by-product from textile wastewater treatment causes a serious problem to be faced in textile industry due to its large amount of production and toxicity characteristic. As an illustration, a textile industry common effluent treatment plant (CETP) in Tripur India generated 200 ton of textile sewage sludge everyday [1]. Even in Leuwi Gajah Indonesia, one of textile industry produces sludge at a rate of 5 ton/day [2]. In order to reduce the volume of sludge, an incineration process by combustion is often carried out. This process is advantageous to eliminating the toxicity problem by heat treatment [3]. Another merit of the process is energy recovery from the result of waste burning in an incinerator [4]. Apart from the beneficial role, the combustion process has a disadvantage of releasing various types of gas, volatile organic compound, dioxin, furan and particulates matter [4]. The flue gas generation is another problem due to the difficulty of keeping emission regulation standards. Sulfur oxide (SO_x) in the form of SO₂ and SO₃ is one of major pollutant releasing from combustion treatment. SO_x has a corrosive characteristic and plays a significant role for occurrence of acid rain when react

with water to form sulfuric acid (H₂SO₄) in the atmosphere. In sewage sludge combustion, the generation of SO_x is coming from oxidation of sulfur compounds belong to material constituent of sludge. Generally the emission derived from the combustion treatment depends on the combustion design, the operational condition and the characteristic of waste [4].

This research tried to investigate the emission characteristic from the material constituent of sludge point of view. In textile industry, the chemical composition of textile sewage sludge depends on heavy chemicals used in textile processing and textile wastewater treatment process. Coagulation, flocculation and sedimentation (clarification process) combined with activated sludge treatment are often used in textile wastewater treatment for color removal and organic removal. In coagulation process, the material called coagulant plays an important role in neutralization of particle surface charge for decolorization process of colored effluent. There are various common coagulants used in wastewater treatment, such as aluminum sulfate (Al₂(SO₄)₃), ferrous sulfate (FeSO₄), ferric sulfate (Fe₂(SO₄)₃) and ferric chloride (FeCl₃) [5]. This research aims to investigate the influence of coagulant species used in a wastewater treatment process on sulfur oxide (SO_x) and other gaseous species emission from textile sewage sludge combustion.

II. MATERIALS AND METHODS

A. Textile Wastewater Treatment Process

The production of textile sewage sludge was modeled on the basis of loadings effluents, daily usage of dyeing materials, heavy chemicals for wastewater treatment and daily production of activated sludge. Material flow and various conditions of a textile wastewater treatment process were referred to a case study in a textile industry in Indonesia [6]. As shown on the scheme of textile wastewater treatment in Fig. 1, there are two types of wastewater derived from textile production activity, colored wastewater and uncolored wastewater.

Firstly colored wastewater was treated in clarification process 1. In this process coagulant FeSO₄ was used for color removal treatment. Lime (CaO) was added to increase the dropped pH after FeSO₄ addition. Polymer ANP-10 was added to form large floc which would accelerate sedimentation process. The treated wastewater from clarification 1 then mixed with uncolored wastewater for biochemical oxygen demand (BOD) and chemical oxygen demand (COD) treatment by activated sludge. The advance

Manuscript received April 15, 2013; revised June 13, 2013.

A. Rahman is with the Department of Environmental Solution Technology, Graduate School of Science and Technology, Ryukoku University, Otsu, Shiga Prefecture 520-2144, Japan (e-mail: t12d501@mail.ryukoku.ac.jp).

N. Kishimoto and T. Urabe are with the Department of Environmental Solution Technology, Faculty of Science and Technology, Ryukoku University, Otsu, Shiga Prefecture 520-2144, Japan (e-mail: naoyuki@rins.ryukoku.ac.jp; urabet@rins.ryukoku.ac.jp).

treatment (clarification process 2) was carried out for suspended solid removal and other contaminants by addition of coagulant $Al_2(SO_4)_3$ and polymer ANP-10 before final discharge to the environment. On the other hand the sludge production from clarification 1, activated sludge and clarification process 2 was pumped to the final sludge tank for sludge treatment.

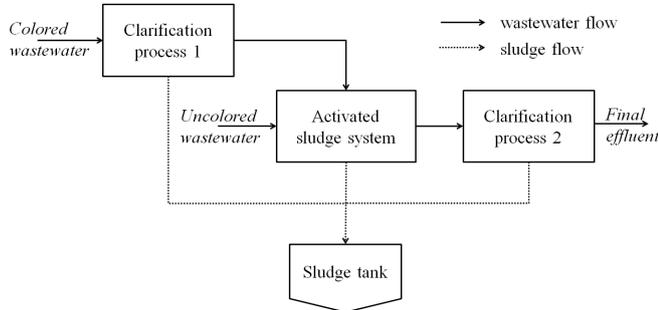


Fig. 1. Scheme of textile wastewater treatment

B. Component of Wastewater and Activated Sludge

The components of textile wastewater are summarized in Table I while the materials used for textile wastewater treatment are provided in Table II.

TABLE I: COMPONENT OF WASTEWATER

		Component	Amount
		Colored effluent	Material
Sodium chloride (NaCl)	32,691 kg/day		
Sodium carbonate (Na_2CO_3)	2,960 kg/day		
Detergent ($C_{12}H_{25}NaO_4S$)	2,018 kg/day		
Uncolored effluent	Condition	Initial COD concentration	432 mg/L
		Discharge effluent	1,200 m ³ /day
Uncolored effluent	Condition	Initial COD concentration	679 mg/L
		Discharge effluent	1,800 m ³ /day

TABLE II: MATERIALS FOR WASTEWATER TREATMENT

Process	Component	Amount (kg/day)			
		Case 1	Case 2	Case 3	Case 4
Clarification process 1	Coagulant ($FeSO_4$)	780	-	780	-
	Coagulant ($FeCl_3$)	-	780	-	780
	Lime (CaO)	270	270	270	270
	Flocculant (Polymer ANP-10)	0.6	0.6	0.6	0.6
Clarification process 2	Coagulant ($Al_2(SO_4)_3$)	675	675	-	-
	Coagulant ($FeCl_3$)	-	-	2,025	2,025
	Flocculant (Polymer ANP-10)	1.5	1.5	1.5	1.5
Activated Sludge ($C_5H_7O_2N$)		12,000			

Whereas the activated sludge components were determined by data in a literature and chemical analysis in the laboratory. The cell composition of bacteria in activated sludge was referred to the literature for prokaryote cell [5]. It is shown in Table III. Laboratory analysis was conducted by using the real activated sludge. Activated sludge was received from municipal wastewater treatment plant in Shiga Prefecture, Japan. Activated sludge content was analyzed by

heating the material in electric furnace for 2 hours at 800 °C. The weight of activated sludge then was compared before and after firing. It resulted that 92% of activated sludge is organic matter content and 8% remain in ash content.

The chemical composition of activated sludge was analyzed with energy dispersive X-Ray spectrometer type EDX-800HS (Shimadzu, Japan). As shown in Table IV the most component of ash in activated sludge was phosphorous pentoxide (P_2O_5).

TABLE III: CELL COMPOSITION AS ELEMENTAL FORMATIONS

Cell elements	Dry weight (%)	Ratio
Carbon (C)	50.0	0.529
Hydrogen (H)	9.0	0.095
Oxygen (O)	22.0	0.233
Nitrogen (N)	12.0	0.127
Sulfur (S)	1.0	0.011
Chlorine (Cl)	0.5	0.005

TABLE IV: CHEMICAL COMPOSITION OF ACTIVATED SLUDGE ASH

Component	Percent of dry based (%)
SiO ₂	11.50
TiO ₂	0.34
Al ₂ O ₃	6.06
Fe ₂ O ₃	2.09
MnO	0.05
MgO	5.05
CaO	8.45
Na ₂ O	4.86
K ₂ O	13.55
P ₂ O ₅	44.95
SO ₃	0.25
Cl	0.00
Cr	0.02
Ni	0.07
Cu	1.73
Zn	0.96
Pb	0.07
Total	100.00

Therefore the activated sludge data as the weight per element and constituent was calculated based on the weight of activated sludge per day (Table V).

C. Sludge Production

As explained earlier in the scheme of textile wastewater treatment there are three main sources of sludge generation consist of clarification process 1, activated sludge system and clarification process 2. Clarification process 1 was carried out for color removal treatment by coagulation and flocculation method. The colored effluent loading is 1200 m³/day with COD of 432 mg/L. The amount of sludge production was calculated from COD removal efficiency, following the equation below:

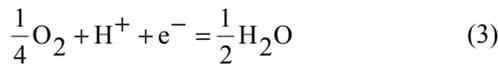
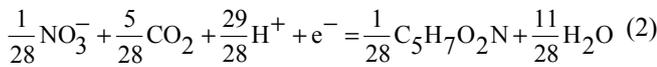
$$SP = (COD_{input} \times IL) - (COD_{output} \times EL) \quad (1)$$

where: SP is sludge production per day (g/day), COD_{input} is the amount of COD before treatment (g/m³), IL is influent loading (m³/day), EL is effluent loading (m³/day), COD_{output} is the amount of COD after treatment (g/m³). From this process the amount of sludge generation is 384 kg/day due to the COD removal efficiency of 74%. Wastewater after decolorization then mixed with uncolored wastewater for biological treatment by activated sludge. According to the

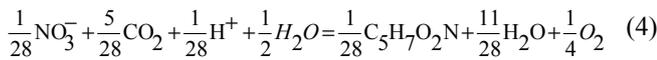
half reaction for biological system [7], the sludge production based on activated sludge system can be estimated by the following equations.

TABLE V: WEIGHT OF ACTIVATED SLUDGE ON ELEMENTAL AND CONSTITUENT

Mass ratio	Element or constituent	Percentage (%)	Ratio	Weight per element or constituent (kg/day)	Weight total (kg/day)
Combustible (0.92)	C	52.91	0.49	5,841.27	11,040
	H	9.52	0.09	1,051.43	
	O	23.28	0.21	2,570.16	
	N	12.70	0.12	1,401.90	
	Volatile S	1.06	0.01	116.83	
	Volatile Cl	0.53	0.00	58.41	
	Total	100	0.92		
Ash (0.08)	SiO ₂	11.50	0.01	110.41	960
	TiO ₂	0.34	0.00	3.23	
	Al ₂ O ₃	6.06	0.00	58.15	
	Fe ₂ O ₃	2.09	0.00	20.06	
	MnO	0.05	0.00	0.49	
	MgO	5.05	0.00	48.45	
	CaO	8.45	0.01	81.13	
	Na ₂ O	4.86	0.00	46.62	
	K ₂ O	13.55	0.01	130.12	
	P ₂ O ₅	44.95	0.04	431.51	
	SO ₃	0.25	0.00	2.42	
	Cl	0.00	0.00	0.00	
	Cr	0.02	0.00	0.21	
	Ni	0.07	0.00	0.71	
	Cu	1.73	0.00	16.58	
	Zn	0.96	0.00	9.20	
Pb	0.07	0.00	0.70		
Total	100	0.08		12,000	



The “(4)” could be obtained from “(2)” and “(3)”.



Refer to “(4)”, 1 mole of C₅H₇O₂N consumes 7 moles of O₂, which means that the conversion factor from COD to the weight of activated sludge is 113/224. Consequently, the sludge production from activated sludge system can be estimated by “(5)”

$$SP = [(COD_{input} \times IL) - (COD_{output} \times EL)] \times \frac{113}{224} \quad (5)$$

In the activated sludge process, COD removal efficiency was 10% that resulted in 69.3 kg/day of sludge production. The clarification process 2 has 46% of COD removal efficiency and 561 kg/day of sludge is produced. Accordingly, the total sludge production from this wastewater treatment flow amounts 1.01 ton/day. The details of COD and sludge production in each process are shown in Table VI.

TABLE VI: SLUDGE PRODUCTION BASED ON COD REMOVAL EFFICIENCY

Process	Wastewater type	COD inlet (mg/L)	COD outlet (mg/L)	Removal ratio (%)	Sludge production (kg/day)
Clarification process 1	Colored	432	112	74	384
Activated sludge system	Colored	112	406	10	69.3
	Uncolored	679			
Clarification process 2	Mixed	406	219	46	561
Total sludge production					1,014.3

D. Material-Oriented Little Thermodynamic (MALT) Calculation

The thermodynamic database of Material-oriented Little Thermodynamic (MALT) calculation was developed firstly in 1986 by Japan Society of Calorimeter and Thermal Analysis [8]. MALT database was constructed to define the chemical behavior based on the chemical thermodynamic data, especially for using in industrial application. The database of MALT stores about 4,932 compounds in gaseous, liquid, crystal and amorphous form [9]. In this simulation we involved 16 elements consist of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulfur (S), chlorine (Cl), phosphorus (P), silicon (Si), aluminum (Al), calcium (Ca), sodium (Na), iron (Fe), potassium (K), lead (Pb), copper (Cu), and zinc (Zn) and there were 765 chemical compounds in the gaseous and condensed form. The air ratio (λ) was carried out at 1.25. Combustion temperature was simulated from 500 °C to 1100 °C. MALT interface for entering initial input simulation is shown in Fig. 2.

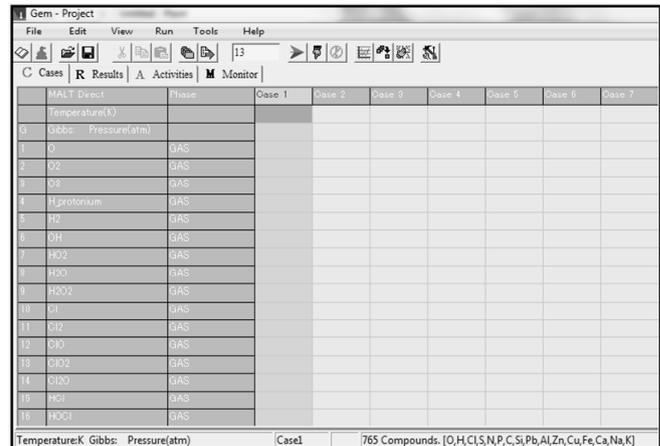


Fig. 2. MALT interface

III. RESULT AND DISCUSSION

A. Material Input for Simulation

We set 4 typical cases of coagulant usage for discussing the influence of coagulant species on emission of gaseous pollutants from combustion process (Table II). In case 1 FeSO₄ and Al₂(SO₄)₃ were used in clarification process 1 and clarification process 2, respectively. The case 1 corresponded to the case study of textile wastewater treatment plant in Indonesia. While in case 2, the coagulant FeSO₄ was changed to FeCl₃ in clarification process 1, but the coagulant used in clarification process 2 was not changed. Bidhendi et al researched that FeCl₃ and FeSO₄ has some optimum doses for

color and COD removal although the optimum pH condition was a little different [10], so dose of FeCl_3 was set at the same with FeSO_4 for simulation. In case 3 FeSO_4 was used in clarification process 1 and coagulant FeCl_3 substituted $\text{Al}_2(\text{SO}_4)_3$ in clarification process 2. The dose of FeCl_3 was set at three times higher than $\text{Al}_2(\text{SO}_4)_3$ because Merzouk et al investigated the removal of synthetic wastewater by chemical coagulation which resulted that the dose of FeCl_3 is three times higher than $\text{Al}_2(\text{SO}_4)_3$ for decolorization purposes [11]. In case 4 FeCl_3 was used both in clarification process 1 and clarification process 2. The compositions of sludge and air ratio for combustion are shown in Table VII. In this research water content of sludge was assumed to have 60% due to dewatering and drying process. The proportion of dissolved component like sodium chloride (NaCl) was referred to the dewatering process of sludge which some amounts transit into wastewater and remain in water on the sludge as 60% of water content.

TABLE VII: MATERIAL INPUT FOR SIMULATION IN VARIOUS CASES

Component	Composition ratio (%)			
	Case 1	Case 2	Case 3	Case 4
Water content	60.039	60.039	59.796	59.796
Combustible matter	34.162	34.162	34.024	34.024
C	18.029	18.029	17.956	17.956
H	3.229	3.229	3.215	3.215
O	7.937	7.937	7.905	7.905
N	4.291	4.291	4.273	4.273
Volatile S	0.458	0.458	0.457	0.457
Volatile Cl	0.219	0.219	0.218	0.218
Ash content	5.799	5.799	6.180	6.180
SiO_2	0.333	0.333	0.331	0.331
Al_2O_3	0.175	0.175	0.174	0.174
Fe_2O_3	0.060	0.060	0.060	0.060
CaO	0.244	0.244	0.243	0.243
Na_2O	0.178	0.178	0.177	0.177
K_2O	0.392	0.392	0.390	0.390
P_2O_5	1.300	1.300	1.294	1.294
SO_3	0.007	0.007	0.007	0.007
Cu	0.050	0.050	0.050	0.050
Zn	0.028	0.028	0.028	0.028
Pb	0.002	0.002	0.002	0.002
Sodium chloride (NaCl)	1.458	1.458	1.452	1.452
Sodium carbonate (Na_2CO_3)	0.891	0.891	0.888	0.888
Coagulant (FeSO_4)	0.235	-	0.234	-
Coagulant (FeCl_3)	-	0.235	-	0.234
Lime (CaO)	0.001	0.001	0.001	0.001
Coagulant ($\text{Al}_2(\text{SO}_4)_3$)	0.203	0.203	-	-
Coagulant (FeCl_3)	-	-	0.607	0.607
Air ratio $\lambda=1.25$	N ₂ (2.702 kg-N ₂ /kg)			
	O ₂ (0.821 kg-O ₂ /kg)			

B. Partial Pressure of Gaseous Species

The partial pressures of the gaseous species as the result of textile sewage sludge combustion at temperature from 500 °C to 1100 °C are shown in Fig. 3. The result was plotted from the case 4 simulation. Sulfur oxide (SO_x) in the form of SO_2 sharply increased with a rise in temperature till 800 °C and reached a plateau over 800 °C. Otherwise SO_3 decreased over 800 °C of combustion temperature. These results accorded

with the literature [12], where SO_3 was more favored at lower temperature whilst SO_2 was favored at higher temperature. Nitrous oxide (NO_x) in the form of NO increased faster than NO_2 with a rise in temperature. When the combustion treatment is performed at a high temperature, the majority of NO_x in flue gas is in the form of NO and then rapidly reacts with oxygen to form NO_2 [12]. The NO_x generated at a high combustion temperature is called "Thermal NO_x " which exponentially increased with a rise of temperature [12]. The hydrogen chloride (HCl) gas slightly decreased with increasing temperature. The partial pressures of other gaseous species are relatively stable and not influenced by the combustion temperature.

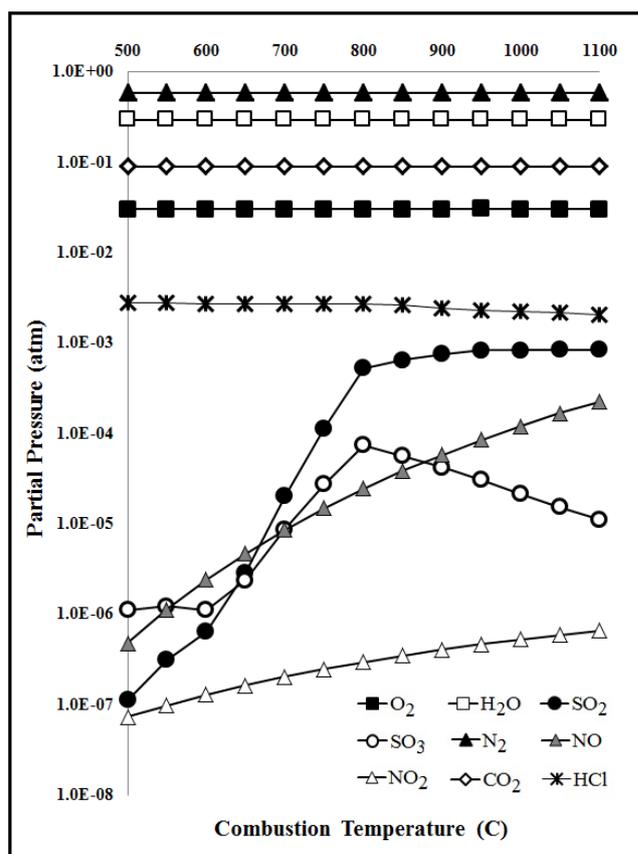


Fig. 3. Variation of the partial pressure of textile sewage sludge combustion as the function of temperature (Case 4)

C. Effect of Coagulant Species for SO_x Generation

As shown in Fig. 4, the concentration of SO_x increased with increasing temperature and reached a plateau over 950 °C for all of cases. The concentration of SO_x in case 4 was lower than other cases. In case 4, 18% of SO_x has been reduced when the combustion temperature was at 850 °C and 19% reduction was achieved over 950 °C if compared with case 1. Although the concentration of SO_x is still high in the case 4, this result indicated that the SO_x production was influenced by coagulant used in the wastewater treatment process. Case 1 contained sulfur element in the form of FeSO_4 and $\text{Al}_2(\text{SO}_4)_3$ of coagulant, otherwise there was no sulfur element in the form of FeCl_3 in case 4. Therefore, sulfur content in the sludge was thought to influence the SO_x production.

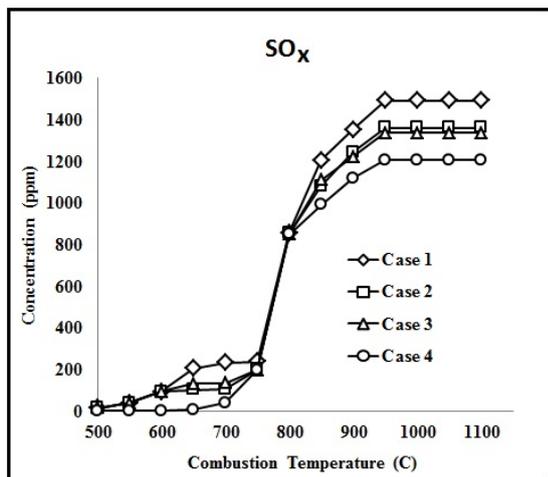


Fig. 4. SO_x generation with temperature as the effect of coagulant type

According to the distribution ratio of sulfur element on Fig. 5, basically the SO_x concentration was relatively low under a combustion temperature of 750 °C. In the beginning sulfur element formed K₂SO₄ and Na₂SO₄ in the condensed form and the both still dominated under a combustion temperature of 750 °C. The gaseous phase of SO₂ began to be dominant species of sulfur compound at the temperature not lesser than 800 °C.

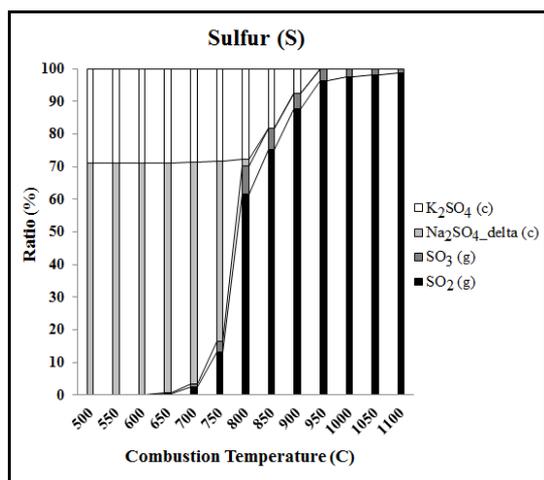


Fig. 5. Distribution of sulfur compound in the condensed phase (c) and gas phase (g) of case 4

D. Effect of Coagulant Species for Other Gases Generation

In contrast to SO_x there was no significant different change of concentration of NO_x for all cases. It can be seen from the Fig. 6 that the simulation resulted in the same concentration of NO_x for all cases. It was due to there were no difference in nitrogen content of the sludge with the change of coagulant from FeSO₄ and Al₂(SO₄)₃ to FeCl₃.

As shown in Fig. 7, the concentration of HCl decreased with a rise of combustion temperature for all cases. According to the distribution ratio of chlorine compound on Fig. 8 HCl were dominant in the lower combustion temperature and its concentration slightly decreased with increasing combustion temperature since the chlorine compound formed such as KCl, NaCl, Cl₂AlO and other formations as increasing temperature. In Fig. 8, the concentration of HCl in case 4 was higher than other cases.

The replacement of coagulant species from FeSO₄ and Al₂(SO₄)₃ to FeCl₃ resulted in an increase the chlorine content in the textile sewage sludge. It enhanced the HCl generation on case 4.

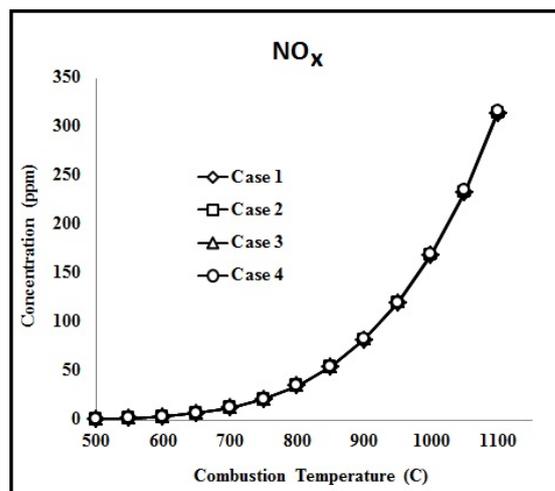


Fig. 6. NO_x generation with temperature as the effect of coagulant type

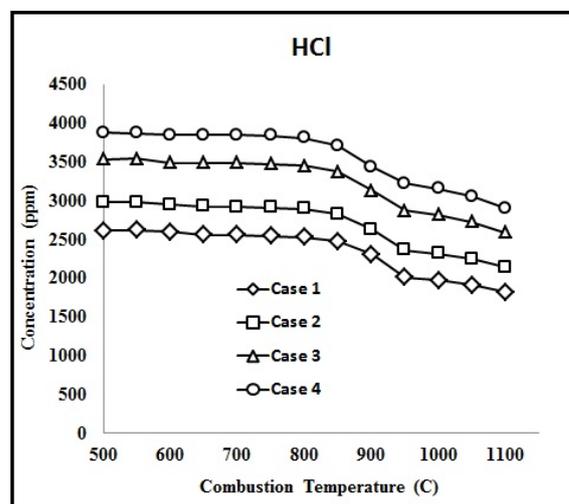


Fig. 7. HCl generation with temperature as the effect of coagulant type

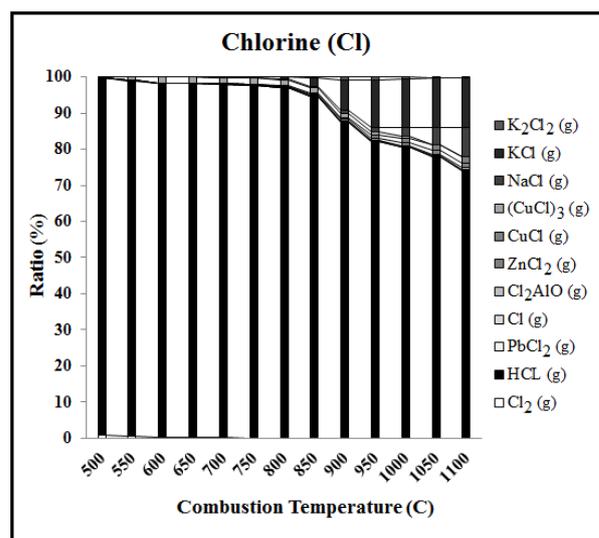


Fig. 8. Distribution of chlorine compound in case 4

Normally carbon monoxide (CO) is generated by the incomplete combustion of a carbon compound with oxygen [12], which may happen if the lack of sufficient oxygen,

insufficient temperature for the entire reaction of CO and inadequate time to complete the combustion process [12].

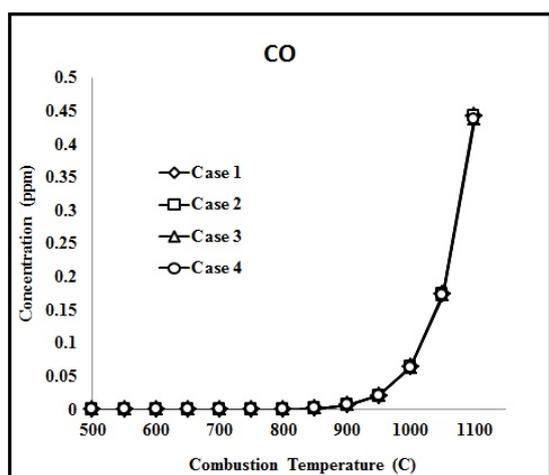


Fig. 9. CO generation with temperature as the effect of coagulant type

As shown in the Fig. 9 the concentration of CO was very low for all cases. It means the oxidizing of carbon compound reached complete combustion. Since MALT assumes infinite combustion time, carbon compounds are completely burned till the depletion of oxygen. In the other hand the trend of CO in Fig. 10 graphically shows similar trend with the adiabatic equilibrium of CO as the function of temperature, which more CO was generated at high temperature due to disassociation of CO₂ into CO [12]. The concentration of CO₂ as the result from this simulation can be seen in Fig. 10. There was no significantly difference of CO₂ concentration as the effect coagulant species change which only 0.5% of CO₂ reduction from case 1 to case 4.

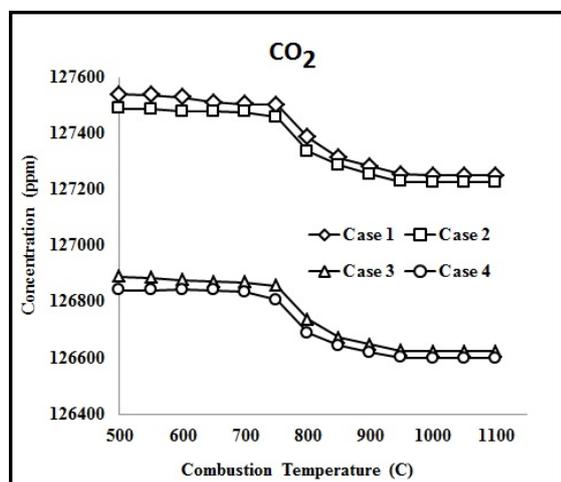


Fig. 10. CO₂ generation with temperature as the effect of coagulant type

E. Other Recommendations for SO_x Minimization

Since SO_x (SO₂ and SO₃) are categorized as a toxic gas and strictly emission standard was imposed on flue gas, SO_x minimization is required in order to meet the emission standard for flue gas. As demonstrated in this research, replacing conventional coagulants to sulfur-free ones is effective to decrease the SO_x emission. However, the SO_x concentration in the flue gas is still high at the combustion temperature over 750 °C. Another possibility to minimize

SO_x generation is by replacing sulfur dyes with other dyes which contain less or no sulfur compound [13]. The sulfur compound on sludge composition will become less by reducing sulfur compound on dyes. Hence the amount of oxidize sulfur during combustion treatment will be minimized also. While from the combustion operating point of view, the control of combustion temperature less than 750 °C has a significant role also for SO_x reduction.

IV. CONCLUSION

The influence of coagulant species for flue gas generation was investigated in this study. Although the SO_x concentration was still high when the combustion temperature was performed more than 750 °C the usage of sulfur-free coagulant successfully decreased SO_x concentration in the flue gas. The simulation demonstrated that case 4 in which FeCl₃ used as a coagulant in both clarification process 1 and 2 could reduce 18% of SO_x generation at the combustion temperature of 850 °C and 19% at the temperature not less than 950 °C compared with conventional case 1 (coagulant FeSO₄ was used in clarification process 1 and Al₂(SO₄)₃ was used in clarification process 2). Otherwise the change of coagulant type did not influence CO₂ and NO_x concentration since carbon and nitrogen contents in the sludge did not change with replacing coagulant species FeSO₄ and Al₂(SO₄)₃ to FeCl₃. Although the replacement of conventional coagulants to sulfur free coagulant of FeCl₃ was effective to reduce SO_x emission by combustion process, the usage chlorine-containing coagulant increased the emission of hydrogen chloride (HCl) gas. Another possibility for SO_x reduction is by controlling the combustion temperature. This research also demonstrated that the control of combustion temperature less than 750 °C could minimize the generation of SO_x in flue gas.

REFERENCES

- [1] J. Balasubramanian, P. C. Sabumon, J. U. Lazar, and E. Ilangoan, "Reuse of textile effluent treatment plant sludge in building material," *Waste Management*, vol. 26, pp. 22-28, 2006.
- [2] A. Rahman and Subari, "Pemanfaatan lumpur ipal industri penyempurnaan basah tekstil sebagai bahan baku produk keramik," *Arena Tekstil*, vol. 23 no. 1, pp 1-4, Oct. 2008 (in Bahasa Indonesia).
- [3] I. S. Turovskiy and P. K. Mathai, *Wastewater Sludge Processing*, New Jersey: a John Wiley & Sons, Inc., ch. 8, pp. 290-302, 2006.
- [4] United States Environmental Protection Agency (EPA), "Combustion emissions from hazardous waste incinerators, boilers and industrial furnaces, and municipal solid waste incinerators-result from five star grants and research needs," Project report, National Center for Environmental Research, Washington DC, USA, Dec. 2006.
- [5] Metcalf and Edy, *Wastewater Engineering: Treatment and Reuse*, 4th edition, New York: Mcgraw-Hill, ch. 6-7, pp. 493-563, 2003.
- [6] A. Herlambang, *Teknologi Pengolahan Limbah Tekstil Dengan Sistem Lumpur Aktif*, Bandung: Textile Research Center, pp 1-16, 2010 (in Bahasa Indonesia).
- [7] P. L. McCarty, "Stoichiometry of biological reactions," *Progress in Water Technology*, vol. 7, no. 1, pp. 157-172, 1975.
- [8] H. Yokokawa, S. Yamauchi, and M. Takafumi, "Thermodynamic database malt2 and its applications to high temperature material chemistry," *Thermochimica Acta*, vol. 245, pp. 45-55, 1994.
- [9] H. Yokokawa, S. Yamauchi, and M. Takafumi, "Thermodynamic database malt for window with gem and CHD," *Calphad*, vol. 26, no. 2, pp. 156-166, 2002.
- [10] G. R. N. Bidhendi, A. Torabian, H. Ehsani, and N. Razmkhah, "Evaluation of industrial dyeing wastewater treatment with coagulants

and polyelectrolyte as a coagulant aid,” *Iran. J. Environ. Health. Sci. Eng.*, vol. 4, no. 1, pp. 29-26, May 2006.

- [11] B. Merzouk, B. Gourich, K. Madani, Ch. Vial, and A. Sekki, “Removal of disperse red dyes from synthetic wastewater by chemical coagulation and continuous electrocoagulation. A comparative study,” *Desalination*, vol. 272, pp. 246-253, Jan. 2011.
- [12] C. E. Baukal Jr, *Industrial Combustion Pollution Control*, New York: Marcel Dekker, Inc., ch. 6-8, pp. 247-402, 2004.
- [13] A. Muezzinoglu, “Air pollutant emission potentials of cotton textile manufacturing industry,” *Journal of Cleaner Production*, vol. 6, pp. 339-347, 1998.



Ari Rahman was born in Bandung, Indonesia on August 22nd 1985. He is now Ph.D student at the Department of Environmental Solution Technology, Faculty of Science and Technology, Ryukoku University, Japan. He received B.Eng from the Department of Industrial Engineering, National Institute of Technology (ITENAS), Indonesia, M.Eng from Department of Environmental Solution

Technology, Ryukoku University, Japan. His research interest are related to the Environmental problem caused by textile industry activities, such as color removal treatment by adsorption, textile sewage sludge recycling, flue gas simulation analysis as the textile sewage sludge combustion.