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Assessment of a Multi-Stage Wet Scrubber Performance Based on Characteristics of Scrubbing Solution

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ABSTRACT

This paper presents the wet scrubber performance on acid gas absorption based on pH and conductivity measurements. The waste combustion system comprised of a CFB combustor in which mainly plastics waste was loaded into the riser (15 cm ID x 1.5 m long). The scrubbing experiments were conducted using a two-stage wet scrubber used as air pollution control device. The performance of the wet scrubber system was assessed by studying the changes in the pH and conductivity. The scrubbing solution was prepared using lime. The optimum lime concentration was obtained from bench experiments, giving an initial pH of up to 13. The scrubbing solution samples were collected from the solution tanks after every 2 minutes for 40 minutes. The scrubbing solution flow rate ranged from 0.53 to 0.95 L/s while the gas flow rate from the blower was kept constant at 16 m/s. It was observed that the pH of the scrubbing solution for both stages decreased to neutral range with increasing operation time. The decrease in pH and conductivity was initially faster before increasing slightly due to deposition of fly ash. It was concluded that the multi-stage wet scrubber is capable of removing toxic acid gas and particulate matter

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INTRODUCTION

Several aspects that relate environment and industrial emission are discussed.

Flue gas cleaning

Due to new legislation worldwide and hefty fines for industries exceeding permitted gas emissions levels, wet scrubbers are one of the flue gas cleaning equipment for protecting the atmosphere and the environment (Speight, 2018).

Flue gas characteristics depend upon the gas flow rate, moisture content, and chemical composition. The flow rate determines the volume of gas to be treated and therefore, the size of the scrubbing system (Manyele, 2008; Said *et al*., 2012). The moisture content and chemical composition are important in determining the pH levels, conductivity, saturation conditions and spent liquid treatment and disposal requirements (Manyele, 2008). The depletion of the scrubbing chemical can be traced by pH and concentration measurements while the changes in the solution properties can be traced by several methods such as conductivity measurements and color or turbidity changes.

Modern air pollution control devices (APCDs) comprise of multiple stage wet scrubbers for the removal of fly ashes, inorganic and organic gases, heavy metals, and dioxins from the flue gas (Vehlow, 2014). Gases that must be removed from combustion systems include sulfur dioxide (SO_2) and a wide variety of by-product and waste gases such as chlorine (Cl_2), hydrogen chloride (HCl), hydrogen sulfide (H_2S) and particulate matter at a range of 2.5 to 10 μm (Rahmpour and Kashkooli, 2004; Huttenhuis *et al*., 2007; Johansson *et al.*, 2017; Yasin *et al.*, 2018).

Wet scrubbers operate by spraying the incoming gas stream with a scrubbing solution containing a scrubbing chemical, which destroys the harmful gas by chemical reaction or physical absorption. The effectiveness of the scrubbing solution in the removal of harmful gases depends on the pH and concentration of the scrubbing chemical (Johansson *et al.,* 2017).

Scrubbing chemical concentration must be maintained to ensure effectiveness of the scrubber. Conductivity and pH can be used to monitor scrubber solution strength/concentration. The operation of wet scrubber involves measurement of parameters such as flow rate, pH, and conductivity. The pH control is critical to the efficient operation of a wet scrubber, because acid gas absorption depends upon the pH of the solvent. An acidic solvent cannot absorb acid gas and causes corrosion to the system, and it may release acidic gases into the environment. Alkaline solvents can absorb acid gases. Excess alkaline in the scrubbing solvent may cause corrosion and scaling of recirculating systems and spray nozzles (Han *et al*., 2019; McGowan, 2016).

However, the chemical nature of the gases in the flue gas determines the choice of absorber solvents (Gumnitsky and Dereyko, 2007). In practice, a single chemical absorbent can be used in one scrubber at a time to absorb several toxic gases. Thus, reagents which can react with several toxic gases are preferable. Lime can absorb most of the acid gases from a combustion system (McGowan, 2016).

Acid gases

Acid gases are flue-gas constituents that form acids when they combine with water vapor, condense or dissolve in water. Acid gases include NOx, SOx, HCl, hydrogen bromide (HBr), hydrogen fluoride (HF), and hydrogen iodide (HI). HCl and SO_2 are often present in uncontrolled flue-gas streams in concentrations ranging from several hundred to several thousand parts per million by volume. The concentration of other gases is typically below several hundred parts per million by volume. There are two sources of NOx from incineration (and other combustion) processes, commonly referred to as thermal NOx and fuel NOx. The thermal NOx is due to a reaction between nitrogen and oxygen during combustion, while the fuel NOx is due to the oxidation of chemically-bound nitrogen in fuel.

Particulate matter

Particulate matter consists primarily of entrained noncombustible matter in the flue gas and the products of incomplete combustion that exist in solid or aerosol form. The solid particle concentration in the flue gas ranges from 180 to more than 46,000 mg per dry standard cubic meter (Matee and Manyele, 2016).

Particulate matter from waste combustors includes inorganic ash present in the waste and carbonaceous soot formed in the combustion process. The fraction of the particulate matter consists of mineral matter and metallic species, which are conserved in the combustion process and leave the combustion chamber as bottom ash or fly ash.

Wet scrubber for medical waste incinerators

Medical wastes include hypodermic needles, body parts, fluids, and laboratory cultures. They are potentially infectious. They require incineration (800-1100°C) to render it harmless rather than burying the waste in landfills or open pit burning (Pépin *et al*., 2014; WHO/UNICEF, 2015). Modern incinerators destroy at least 99.9% of the organic waste materials they handle.

Medical waste incineration produces mainly NOx, SO2, CO, CO2, HCl, and organic gas like dioxins and furans (Sharma *et al*., 2019). The gases are dangerous to human health and the environment, necessitating the application of high technologies to remove the gases from the flue gas stream.

For highly water-soluble acid gases, a single Stage of wet scrubber is enough to remove them, but for slightly water-soluble acid gases, multi-stage wet scrubbers are more applicable (Gingerich *et al.*, 2018; Huttenhuis *et al*., 2007; Rahmpour and Kashkooli, 2004; Nolan, 2000).

Incomplete combustion products, fly ashes, and heavy metals such as mercury, lead, arsenic, and cadmium are also incineration products. They are a fraction of the flue gas stream (Liu *et al.*, 2018; Matee and Manyele, 2016). There are several types of wet scrubbers, but this study focuses on spray tower scrubbers incorporating nozzles.

pH control

Increased absorption efficiency is achievable at high pH values since more alkali is available to neutralize the acid gas. However, scale buildup will occur if the scrubber is operated at very high pH values, while low pH reduces removal efficiency. More than a dozen different reagents have been used, with lime and limestone being the most popular. The sodium-based solution provides better SO2 solubility and fewer scaling problems than lime or limestone. However, sodium reagents are much more expensive. The pH levels of the solvents should not operate above a pH of 8.0 to 9.0 (Chen and Xu, 2005).

The pH control is often the choice for scrubbers using continuous blowdown and replenishment. Acidic gas scrubbing, such as hydrochloric acid (HCl), is controlled by maintaining an excess concentration of an alkaline scrubbing chemical, such as caustic (NaOH) or lime ($Ca(OH)_2$). The pH is specific to hydrogen ion (H+) concentration, which is related to the amount of the alkaline scrubbing chemical. This specificity allows pH to control scrubbing with minimal effects from scrubber by-products. The pH response curve follows a strong acid/base titration curve.

Conductivity control

Conductivity is best suited to measure scrubber solution concentration in batch scrubbers. It is more accurate when the gas stream contains only one soluble gas. For more than one gas, difficulties can arise. Estimating the amount of flue gas absorbed from conductivity is difficult, although a conductivity measurement may still provide an alarm point to alert the operator to check a grab sample. The conductivity indicates to initiate blowdown to prevent a buildup of dissolved solids in continuous replenishment scrubbers.

Chemistry of the acid gas removal in the scrubber using lime

The alkaline slurry of limestone reacts with the acid gases in the flue gas, such as CO2 and HCl (shown in chemical reactions (Equations (1) and (2)) based on literature (Liu *et al*., 2001; Rahmpou and Kashkooli, 2004; Huttenhuis *et al*., 2007; Tillman *et al*., 2009)

$$\begin{aligned} &2HCl + CaCO_3 \rightarrow CaCI_2 + H_2O + CO_2 \\ &2H^+ + CaCO_3 \rightarrow Ca^{2+} + H_2O + CO_2 \end{aligned} \tag{1}$$

$$\begin{aligned} &CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2(H_2CO_3^-) \\ &CaCO_3 + 2(H_2CO_3^-) + Ca^{2+} \rightarrow 2Ca(HCO_3)_2 + 2H_2O \end{aligned} \tag{2}$$

Experiments of co-combustion of RDF and coal in a vortexing fluidized bed described by Chiang *et al*. (2010) and Kim *et al*. (2010) reported a decrease of HCl in the flue gas in the presence of CaCO3. Acid gases can also react with lime leading to calcium salts and water, as shown in Equations 3), (4), and (5), respectively.

$$2HCl + Ca(OH)_2 \rightarrow CaCl_2 + H_2O \tag{3}$$

$$2HF + Ca(OH)_2 \rightarrow CaF_2 + H_2O \tag{4}$$

$$SO_2 + Ca(OH)_2 \rightarrow CaSO_3/CaSO_4 + H_2O \tag{5}$$

When wet scrubbing with a $Ca(OH)_2$ (lime) slurry, the reaction between CO_2 and lime takes place, leading to $CaCO_3$ precipitate, as per Equation (6):

$$Ca(OH)_2\,(solid) + CO_2\,(gas) \rightarrow CaCO_3\,(solid) + H_2O\,(liquid) \tag{6}$$

The reaction also produces $CaSO_3$ (calcium sulfite) and can be expressed as per Equation (7):

$$Ca(OH)_2\,(solid) + SO_2\,(gas) \rightarrow CaSO_3\,(solid) + H_2O\,(liquid) \tag{7}$$

Scrubbing solution wastewater management is another key aspect which must be considered during design and operation of wet scrubbers. Water from flue gas scrubbers and ash washing which contains mercury, heavy metals and salts can be precipitated with lime and trimercaptotriazine (TMT15) in two stages to produce an effluent that meets the strong discharge standards of the FRG (Reimann, 1987).

METHODS AND MATERIALS

Process description

The process consisted primarily of preparing feed waste for combustion and scrubbing solution, adjusting gas and liquid flow rates, and operating the sampling and analytical equipment to record data. Scrubbing liquid water and/or aqueous lime solution was prepared in the liquid feed tanks, T_{w1} and T_{w2}, as shown in Figure 1 (Said *et al*., 2012). Reagent lime was mixed with water to make up the feed solution to the wet scrubber. The scrubbing liquid, initially at a pH of about 11, measured by using a pH meter, was fed to the scrubber using a centrifugal pump. The cooling water was also circulated into the heat exchanger by pumping while adjusting the valves until the desired flow rates were reached. Gas flow was started by switching on the blower and adjusting the gas flow rates, *G*, using the opening a flap on the suction side of the blower.

The test series consisted of runs with gas at a speed between 4 and 14 m/s and liquid flow rates ranging from 0.15 to 0.95 L/s. The exhaust gas velocity was kept low, from 0.3 to 1.2 m/s to prevent excess droplets from being carried out of the tower. Different combinations of gas and liquid flow rates (*L/G*) were used. Experiments were designed to measure pH variation in the scrubbing solution tank by taking samples from solution feed tanks every minute during the operation time of 40 minutes. Each run, the same amount of waste was loaded in the combustion chamber, that is, 1.5 kg of mixed plastic and wood wastes with similar proportions (30% plastic and 70%wood waste).

The flue gas from the combustion chamber exits the riser and passes through a series of cyclones (for removal of solid particles), heat exchanger (for reducing temperature to about 80°C) and finally passes though the multi-stage wet scrubbers for removal of acid gases and particulate matter. The exhaust gas stream enters the bottom of the tower and moves upward, while liquid is sprayed downward (countercurrent flow) (Manyele, 2008). The liquid is re-circulated until it is exhausted and can no longer capture acid-gases. Figure 1 shows the circulating fluidized bed incineration facility with multi-stage wet scrubbers used in this study.

Determination of Scrubbing Solution pH

The pH meter connected to the electrode was used to measure the ph of the sample obtained at different time intervals. Increased absorption efficiency is achievable at high pH values since more alkali is available to dissolve the acid gases. The decrease in pH values of the scrubbing solution indicates how well the acid gases are absorbed.

Determination of the Liquid Recirculation Rate

The time required for the scrubbing solution to be completely circulated across the scrubber Stage, R_t, was calculated based on Equation (8):

$$R_t = \frac{V_t}{Q_{in}} \tag{8}$$

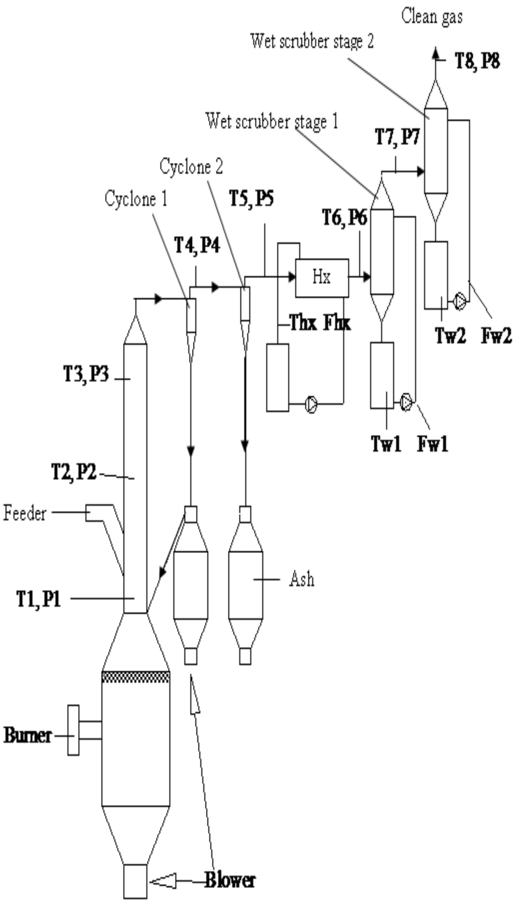

Figure 1: Experimental set up for a multi-stage wet-scrubber unit with cooling system and cyclone dust collectors.

where V_t = volume of scrubbing solution tank and Q_{in} = scrubbing solution inlet flow rate.Thus, the total number of cycles during incineration cycle time, N_{ct}, is given by Equation (9):

$$N_{ct} = \frac{T_c Q_{in}}{V_t} \tag{9}$$

where T_c is the incineration cycle time. Note also that N_{ct} is an indication of how many times the solution is recirculated between the tank and the scrubber, which can be related to mixing and turbulence in the scrubber.

Determination of Lime Dosage Range for Preparing Scrubbing Solution

To establish the optimum lime concentration for use in scrubbing, the pH of the scrubbing solution was measured at different lime concentration from as low as 0.1 to 20 g/L, as shown in Figure 2. As expected, the pH increased with increasing lime concentration reaching above 11 depending on the strength of the lime used. For lime concentration from 6 g/L and above, the pH remained constant for both tap water (TW) and distilled water (DW).

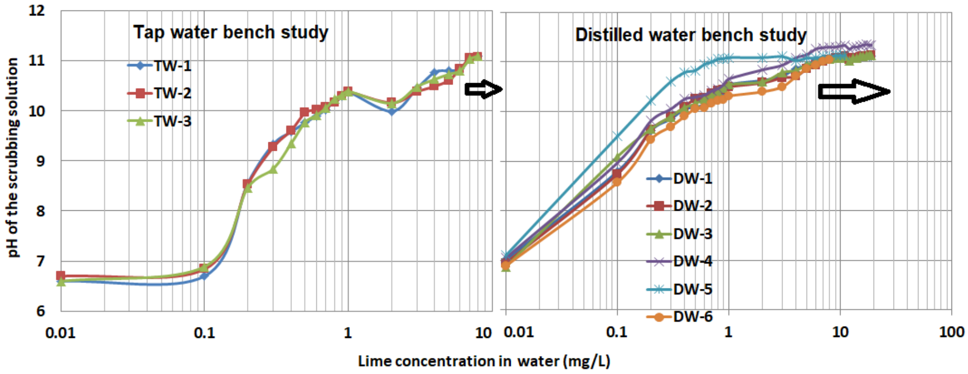

Figure 2: Variation of pH with different amount of limestone added in tap water (TW) and distilled water (DW) measured at different runs.

More lime was added in both DW and TW even when the pH was already constant in order to test whether there were any notable changes. The increase in pH was delayed when tap water was used in the bench scale tanks. In actual operation, tap water is normally used, hence, scrubbing solution was prepared using TW for the rest of experiments.

From the results, the ultimate values for tap and distilled water were almost the same with the maximum pH being 11. It was generalized that the optimum/maximum lime concentration to use is 6 – 15 g/L. In practice, the solution tanks used are plastic tanks of capacities of 100, 500, 1000, 2000 or 5000 L. Thus, for a concentration range of 6-15 mg/L, it is possible to quantify the amounts of lime required in kg for a given tank size. This quantity was calculated as per Equation (10):

$$L_{wt} = \frac{C_L V_t}{1000} \tag{10}$$

where L_{wt} = required weight of lime in kg; C_L = required lime concentration (g/L) and V_t = tank volume (L), as defined above. Figure 3 summarizes the data on required lime quantities, L_{wt}, as a function of scrubbing solution tank volume, V_t, on a log-log plot for $C_L = 6 – 15$ g/L.

Preparation of scrubbing solution for conductivity measurements

The conductivity for both distilled and tap water was observed to increase with lime concentration. This is because conductivity is a measure of how well solution conducts electricity, which means water with absolutely no impurities conduct poorly compared with water that contains impurities. Choosing lime dosing within the range of 6–15 g/L means the conductivity of the scrubbing solution willow about 4-7 µS/cm. Because impurities in water increase conductivity, the conductivity scrubbing liquid is expected to be large due to trapped ash and acid gases.

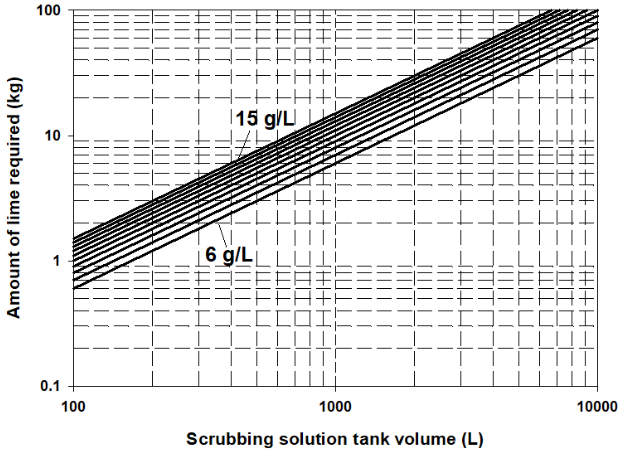

Figure 3: Quantities of lime required to make scrubbing solutions of different concentrations for various solution tank volumes.

RESULTS AND DISCUSSION

Temperature profiles in the riser during waste combustion

Figure 4 shows the temperature profiles in the combustion chamber during incineration cycles. The plot shows five runs of 40 minutes long, characterized by highest or peak temperature and horizontal peak location. The temperature in the combustion chamber increased towards the peak, in 5 to 10 minutes, before decreasing again. The profiles are similar in shape, with the peak values ranging between 450 and 650°C. All profiles follow the same paten of temperature variation, showing differences in peak values and time to reach the peak, as well as differences in decrease in temperature after completion of combustion, depending on the air flow rate from the blower and also on the peak value reached. An interesting behavior was observed during the incineration time between 4 to 12 minutes whereby, temperature fluctuations occurred as the temperature approached the maximum values.

It is also during the first 10 minutes of incineration time in the scrubbing solution properties in terms of pH and conductivity as described later. The temperature profiles can be characterized further based on peak values and combustion chamber cooling rate after the peak. All these characteristics depend on waste properties (composition and moisture content, average particle size) and aeration rate from the blower.

Variation of scrubbing solution pH with time during waste incineration

Effect of lime on flue gas scrubbing performance

The change in pH of the scrubbing solution was studied at different operating conditions such as scrubbing liquid inlet flow rate into the scrubber, Q_{in}, recirculation rate, R_c, scrubbing with and without lime; time delay from solution preparation to scrubbing operation.When scrubbing liquid containing lime was used, the pH dropped from about 12.5 to a lowest value of about 7.5 in a short time of about 8 to 12 minutes, as shown in Figure 5. Such a drop of pH occurs when the temperature in the combustion chamber is still increasing and the combustion process is at its infant Stage. Beyond 12 minutes, the pH increases again slightly.

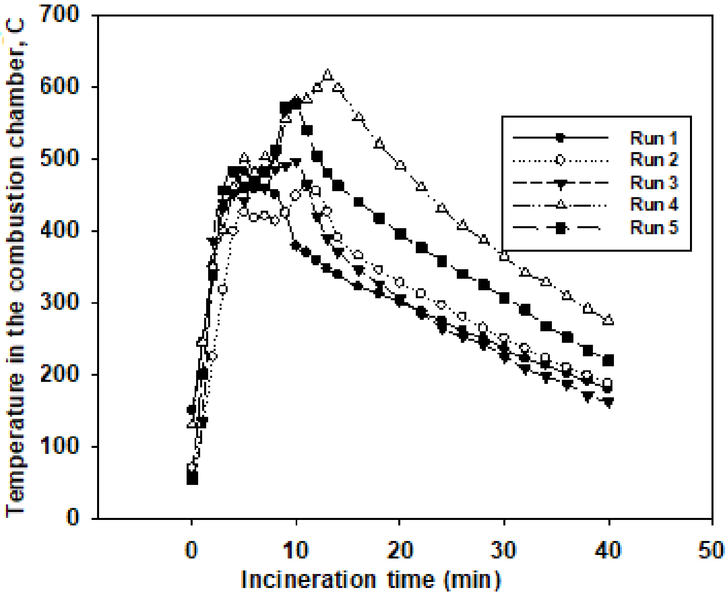

Figure 4: Temperature profiles in the combustion chamber during incineration of solid waste.

The drop in pH indicates that the acid gases generated at lower temperatures in the combustion chamber are reacting with lime in the solution, leading to a neutral solution. Meanwhile, the slight increase in pH beyond 12 minutes can be attributed to the alkaline fly ashes which are blown off by a blower (once formed in the combustion chamber) and trapped by the scrubbing solution, thus increasing the pH of the solution. In that time range, the temperature is already reaching the maximum, and the acid gases are generated to the minimum.

Figure 5 shows also that when water is used, the pH is slightly constant initially, but then starts to increase from 8th minute, with ultimate values approaching those of a solution prepared using lime. It can be generalized that, when the water is used as scrubbing solution, it has low capacity of absorbing the acid gases and pH remains constant. But when fly ashes are captured, the pH starts to increase. The ultimate pH is the same when scrubbing with either lime solution or water, indicating that the lime is already spent out leading to neutral solution, which resembles water, being equally affected by fly ashes. Since the ultimate pH values approach common values after 15 minutes, with and without lime dosing, the role of lime is therefore important at the initial stages of a batch combustion process after which fly ash dissolves in the solution leading to an alkaline solution and dominates the scrubbing role, as the pH remains relatively constant between 7.5 and 8.2.

Effect of initial scrubbing solution pH on wet scrubber performance

Figure 6 is a comparison between pH profiles of the scrubbing liquid (a) prepared with lime and used immediately (S1) and (b) prepared with lime and used next day (S2). The difference between the two solutions was the initial pH of 12.2 and 8.6 for S1 and S2, respectively. The solution denoted as So was tap water used without lime dosing.

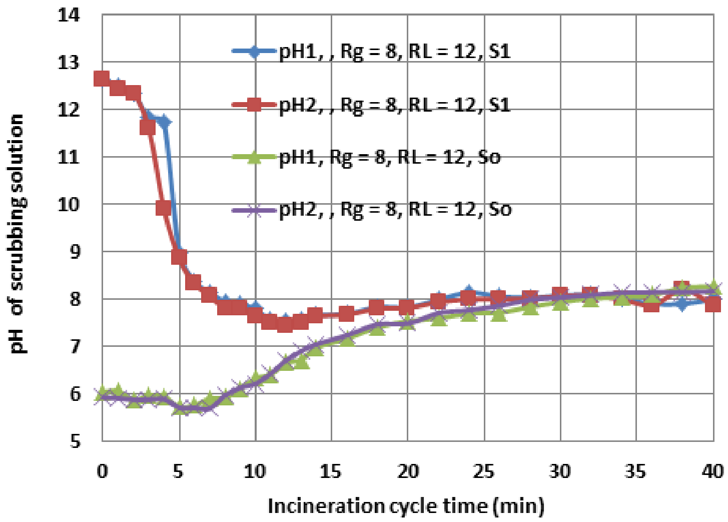

Figure 5: Variation of scrubbing solution pH with incineration time (with and without lime).

The liquid inlet flow rate in the scrubber was 0.721 L/s in both cases. While the S1 data resembles the data presented in Figure 5, the S2 profiles behaved differently initially.

Starting with pH of 8.5 for the S2 solution, the pH decreased to 7.5 in 3 minutes of combustion process similar to the S1 solution, whose pH dropped from 12.2 to 7.5 in 3 minutes as well. Afterwards, the two solutions behaved similarly, decreasing pH down to the common minimum of 7.0 in 10 minutes and then increasing slowly to an ultimate value of 8.5 for the rest of the incineration cycle.

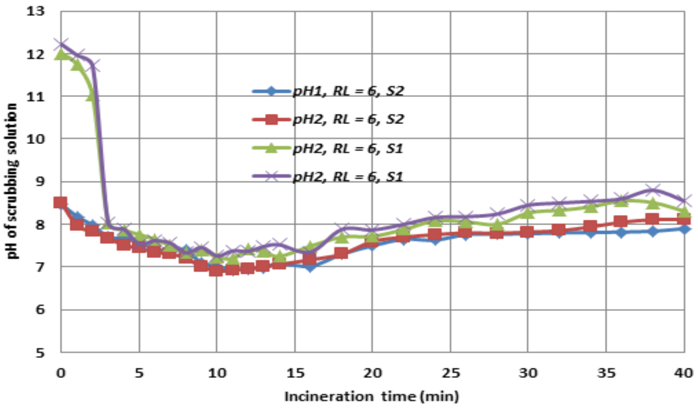

Figure 6: Effect of initial scrubbing solution pH on scrubber performance.

The initial pH at the starting of the incineration cycle is well above the recommended range of 8.0 to 9.0 for S1 (Chen and Xu,2005), which however, drops to the allowable operating range in short time of less than 3 minutes, as shown in both Figures 5 and 6. When the scrubbing solution S1 was used, the pH dropped from 12.2 to 8.0 immediately in 3 minutes, indicating a faster consumption of lime during initial combustion stages. This can be attributed to low temperature in the combustion chamber which rises from 100 to 500°C initially generating more acid gas emissions. The pH for S2 decreased slowly from 8.6 to 6.8 in 10 minutes before increasing due to fly ash also to an ultimate pH of 8.5. Thus, the S2 solution had low scrubbing capacity than S1, although the two solutions had similar ultimate pH values. After 3 minutes of scrubbing solution recirculation, the two solutions S1 and S2 behave similarly. The values of pH for Stage 1 were higher throughout the scrubbing cycle, attributable to capture of most of the fly ash from the combustion chamber in the first stage. The variations of pH with time in different stages of the multi-stage wet scrubber were the similar indicating that each stage behaves the same with slight difference in the pH values. This indicates further that Stage 1 was not good enough in flue gas cleaning leading to the need for a second stage.

Effect of wet scrubber operating conditions

Figure 7 compares the profiles of pH at different operating conditions studied. The pH data was collected for each of the two stages (denoted as pH_1 and pH_2, respectively). The scrubbing solution inlet flow rate was increased from RL = 4, 8 and = 12, for three different runs. Most of the profiles behaved in the same manner except for the solution prepared without lime. The lime solution used immediately, S1, shows higher initial pH between 12 and 13 drop immediately to about 7.5 in 10 minutes of scrubbing operation, before increasing slowly to the ultimate value above pH = 8.0. The initial pH for So was about 8.5, which dropped also to 7.5 in 5 minutes before increasing slowly to the same ultimate pH value similar to S1. In all cases, the scrubbing solution pH approaches 8.0 or above at the end of the combustion process, regardless of the initial pH conditions, making the solution useful in the next runs.

Profiles of scrubbing solution pH in different stages of the wet scrubber

Figure 8 compares the profiles of pH of the scrubbing solution during incineration cycles based on solution S1 at different scrubbing solution inlet flow rates. In all cases, the profiles are compared for cycler times starting from 10 to 40 minutes, when the pH starts to increase due to capture of fly ash, (which is alkaline) from the combustion chamber. The profiles do not show remarkable difference between stages at R_L = 12 that is, higher solution inlet flow rate, while pH_2 values were higher than pH_1 at R_L = 8. Thus, the pH profiles in the two stages depend strongly on the inlet liquid flow rate. Moreover, at R_L = 4, 6, and 8, the ultimate pH values were about 9.0, which allows there-use of the solution in the next run.

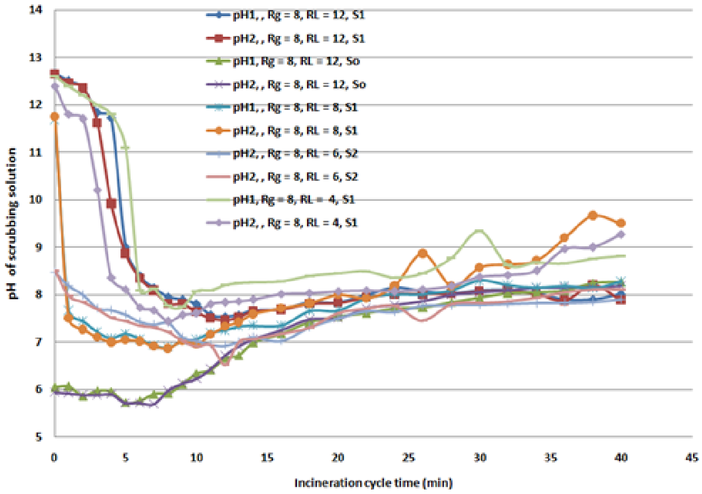

Figure 7: The pH profiles at different operating conditions and initial solution properties

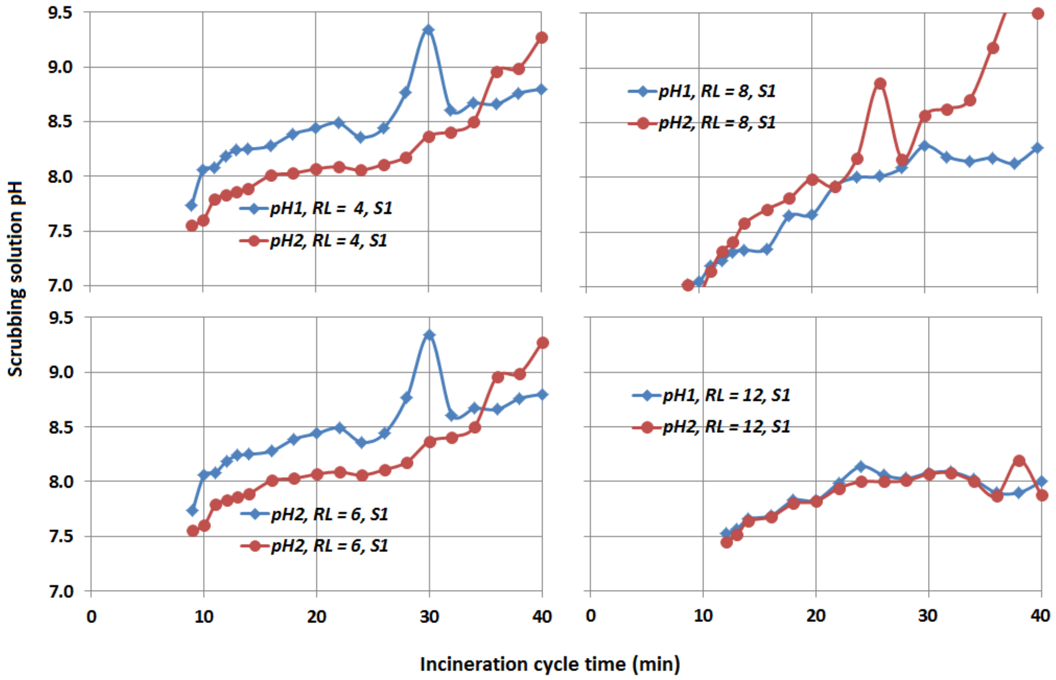

Figure 8: Profiles of pH of the scrubbing solution for stages 1 and 2 during flue gas scrubbing process.

Profiles of the scrubbing solution pH or consecutive incineration cycles

Figure 9 shows the pH profiles for scrubbing solution used for three consecutive incineration cycles. In this case, the same solution was used for three consecutive incineration cycles loaded with the same type and quantity of waste. In the first cycle, the initial pH was 11.0, with a minimum pH of 8.0 and a final pH of 8.4 at the end of 35 minutes. The pH profiles in the first cycle or run behaved similar to data presented in Figures 5, 6 and 7 for S1 solutions. Both Stages 1 and 2 had similar profiles as reported earlier. The final pH ultimately reached, allowed re-use of the solution without adding or dosing with extra lime. In this case the ultimate pH values in Run 1 and Run 2 were 8.4 and 7.3, respectively. The spent solution was subjected to a second incineration cycle, in which the pH dropped from 8.4 to the minimum of 6.9 for Stage 1 and to 6.8 for Stage 2, before increasing again to constant values of 7.3 and 7.2, respectively. The final conditions after the second incineration cycle were almost neutral, with distinct pH values for Stage 1 and Stage 2 scrubbing solutions.

The pH profiles when the scrubbing solution from second cycle was subjected to a third cycle shows that the pH changed from 7.3 and 7.2 to a common minimum value of 6.5, before increasing again to a common and constant ultimate value of 6.9. The last cycle was operated in neutral pH zone with the small change in pH, indicating that the flue gas treatment was less effective.

The first run for the scrubbing solution is operated with the lime having pH still in the accepted range of 8.0 to 9.0. It is evident from Figure 9 that the first run uses a stronger solution than the last two runs. It should be noted that the time intervals between the runs were removed in Figure 8, although a time delay is inevitable for preparation of the feed materials, loading and startup, which can allow the unbuffered solutions to react further.

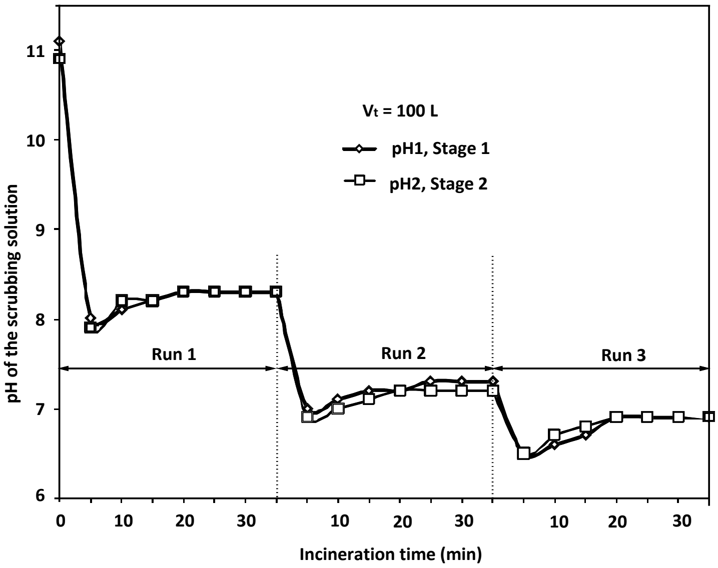

Figure 9: The pH profiles for scrubbing solutions (Stage 1 and 2) subjected to successive incineration cycles.

Detailed analysis of pH profiles during incineration cycles

Defining ΔpH° as the change in pH from the highest initial value to the lowest minimum reached within the first 10 minutes of scrubbing operation, it was observed that this change decreased with increasing number of runs from 3.1, 1.3 to 0.8 for first, second and third cycle, for Stage 1. This is associated with initial flue gas quality at low temperature of the combustion chamber (Figure 4).

Also defining ΔpH^f as the change in pH between the initial value and the final value at the end of the scrubbing operation, then, with increasing number of runs, ΔpH^f decreased from 2.8, 1.0 to 0.4 for runs 1, 2 and 3, respectively, for scrubbing solution in Stage 1. Meanwhile, for Stage 2, the values of ΔpH^f were 2.6, 1.1 and 0.3 for runs 1, 2 and 3, respectively. As stated above, the scrubbing solution is usually re-used several times, until it is completely exhausted, especially for expensive dosing chemicals like NaOH and $Ca(OH)_2$. The final pH values, pH^f, also changes between runs. For a single run, it depends on operating conditions set for liquid recirculation rate, gas flow rate, and initial solution concentration. Thus, the incinerator can be operated for few cycles using the same solution, if the initial pH values are well monitored. Table 2 summarizes the values of ΔpH^o and ΔpH^f for both Stages.

Table 2. Values of of ΔpH^o, ΔpH^f and pH^f for scrubbing solution.

Run No.	Stage 1			Stage 2		
	ΔpH^o	ΔpH^f	pH^f	ΔpH^o	ΔpH^f	pH^f
1	3.1	2.8	8.3	3.0	2.6	8.3
2	1.3	1.0	7.3	1.4	1.1	7.2
3	0.8	0.4	6.9	0.7	0.3	6.9

Based on pH^f data, if the value reached is not sufficient to carry out another run, it is possible to add more lime to re-activate the solution. However, dosing requirements need a separate study. The very low pH values reached within 10 minutes of incineration time correspond to time for the temperature to reach the maximum (which indicates the completion of combustion materials). This indicates that there is no more acid gas generation in the combustion chamber and that only fly ash is captured in the scrubbiong solution, leading to rise in pH. The minimum pH values reached were already outside the optimun pH range of 8.0 to 9.0, by the time the burning wastes are completed. This indicates that the scrubber is performing well in terms of acid gas aborption. Dropping the pH immediately from around 12.0 to 7.0 within 10 minutes of incineration or scrubbing operation time shows that the combustor destroys the waste faster to ashes.

It was further revealed that the values of ΔpH^o, ΔpH^f and pH^f depend on oprating conditions for the wet scrubber, especially liquid recirculation rate, R_t, or the total number of cycles (through the wet scrubber) undertaken by the scrubbing solution, as summarized in Figure 10.

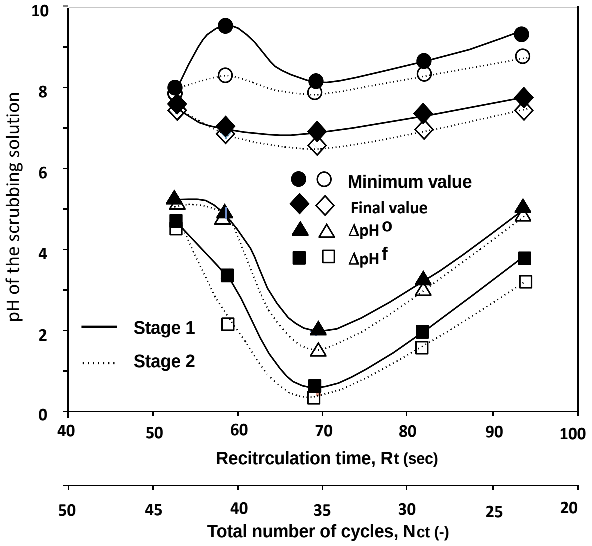

Figure 10. Effect of scrubbing solution recirculation rate on the pH changes.

Based on Figure 10, both ΔpH^o and ΔpH^f show a minimum turning point at a recirculation rate corresponding to 70 seconds or a total number of cycles, N_{ct} equal to 35 for scrubbing solutions in both Stage 1 and 2. Thus, higher values of ΔpH^o and ΔpH^f should be avoided for proper wet scrubber performance in the removal of acid gases. In this case, the values of R_t = 70 sec and N_{ct} = 35, gives the optimum scrubbing liquid flow rate, as they lead to lowest changes in the scrubbing solution pH. Higher values of ΔpH indicate that the solution is exhausted faster and may require dosing or stringent process control system for continuous scrubbing process. The fact that fly ashes improve the solution properties towards toxic acid gas capture, and maintenance of a constant pH value towards the ultimate value, is a critical observation, which eliminates the need for control systems in batch incineration and scrubbing systems.

With reference to Figure 8, reusing the scrubbing solution without dosing is thus not effective and lowers the scrubber performance since the pH will be below the allowable alkaline or pH range. Moreover, with reference to Equations (1) and (2), the optimum inlet liquid flow rate, Q_{in}^o, depends on the tank volume. The values of Q_{in}^o can be established for given tank volumes as shown in Figure 11.

The optimum scrubbing solution flow rate can be estimated using Equation (11):

$$Q_{in}^{o} = 0.014V_t \qquad (11)$$

Thus, large solution tank capacity allows the scrubber operation to be conducted at higher inlet liquid flow rate, and allows the operation at higher optimum liquid flow rate as well, when the number of cycles and recirculation rate are kept constant, depending on the minimal pH changes during scrubbing operations.

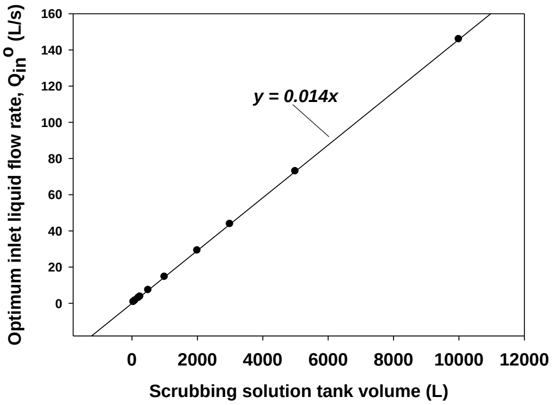

Figure 11: Optimum scrubbing liquid flow rate based on pH data for different tank volumes.

The need for pH control

It should be noted that pH control is often the choice for scrubbers using continuous blowdown and replenishment of the alkali. Acidic gas scrubbing, such as sulfur dioxide (SO_2), is controlled by maintaining an excess concentration of a basic scrubbing chemical, such as caustic (NaOH) or lime ($Ca(OH)_2$). Since pH is specific to hydrogen ion concentration (H^+), which is related to the concentration of the basic scrubbing chemical (high pH means low H^+ concentration), it can be used to control scrubbing with minimal effects from scrubber by-products. If the scrubber uses strong caustic (10-15% NaOH), pH control is not suggested since the exposure of the pH glass to high concentration of caustic will cause dissolution of the pH glass, thus destroying the electrode. The pH response curve follows a strong acid/base titration curve, which results in a reading that only drops back on-scale near a point of complete exhaustion of the caustic, followed by a sudden drop at the exhaustion point.

Variation of the conductivity of scrubbing solution with incineration cycle time

Conductivity of scrubbing solution during incineration process

During data collection, scrubbing solution performance was monitored by conductivity measurements with time, as presented in Figure 12. Using the whole cycle time (Figure 12), results show that the conductivity of the scrubbing solution dropped abruptly from 4500 to the minimum of 470 µS/cm within 4 minutes, after which conductivity increased to a maximum of about 900 µS/cm at t = 12 minutes. This was followed by a decrease in conductivity to 650 and 750 µS/cm for both stages, respectively.

The insert in Figure 12 shows the details of conductivity profiles for S1 in the two stages after the minimum point, beyond 5 minutes of incineration cycle time.

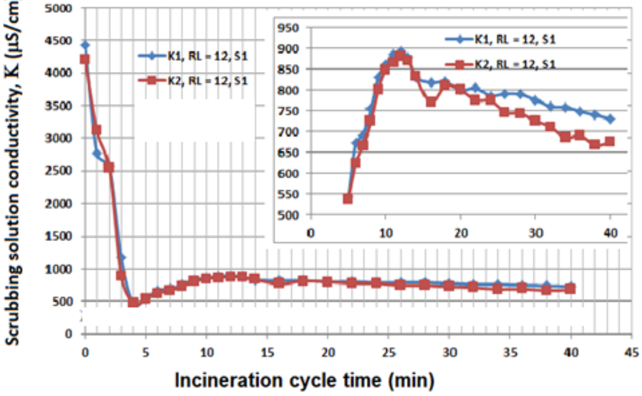

Figure 12: Variation of scrubbing solution conductivity during waste incineration at a fixed inlet solution flow rate.

Figure 13 shows the variation of scrubbing solution conductivity with time during waste incineration for both stages and for both S1 and S2, at R_L = 6. Addition of lime to the tap water increased the initial conductivity of the scrubbing solution for both stages. Using lime water as a scrubbing liquid immediately after preparation, higher values of conductivity were observed in scrubbing solution compared to those obtained when the solution is stored overnight, as shown in Figure 8. Impurities in water increase its conductivity. The increase in conductivity after the minimum point shows that the scrubber performs well in removing pollutants for both acid gases and particulate matter (which are mainly fly ash).

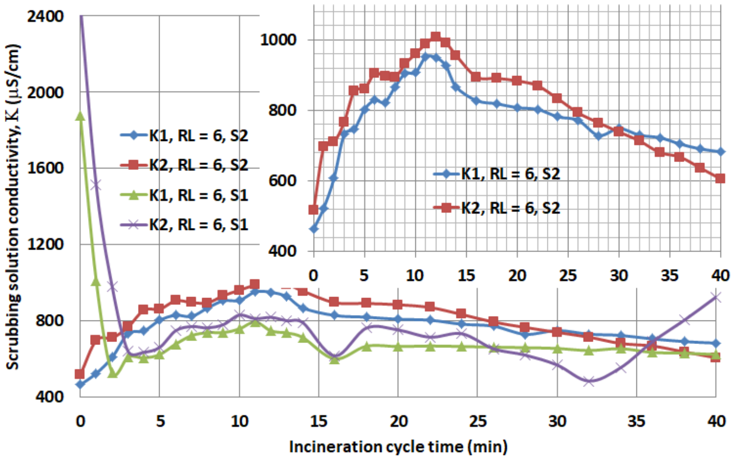

Figure 13: Effect of initial solution conductivity (S1 and S2) on scrubber performance during waste incineration at constant inlet solution flow rate.

The conductivity data for incineration cycle times of 40 minutes suits well because the process was carried out batchwise. Since the combustion chamber runs one load at a time, the wet scrubber stages are also regarded as batch scrubbers. It has been observed that conductivity start with minimum value, then increases as the incineration continues and finally decreasing again. This can be explained based on the fact that, initially, the solution reacts with acid gases produced at lower chamber temperatures, lowering conductivity within short time. The solution then starts to capture inorganic compounds as fly ash increasing the conductivity, but also capturing acid gases, hence, a rise in in conductivity. Afterwards, the fly ash does not reach the wet scrubber stages and the conductivity decreases again from 12 minutes to 40 minutes.

As mentioned previously, conductivity is nonspecific and will respond to both conductive scrubbing chemicals and by-products. As the scrubbing chemical is depleted, its contribution to the scrubber solution conductivity will decrease. At the same time that the chemical concentration is being depleted, the by-products are building up and their contribution to the total conductivity is increasing, for the period of 4 to 12 minutes. During waste incineration, more than one acid gas is generated and scrubbed, leading to a large number of byproducts in the spent scrubbing solution or effluent.

Variation of the conductivity of scrubbing solution

Similar to data presented in Figure 8, the conductivity of scrubbing solution used for three consecutive runs is presented in Figure 14. During the first run, the scrubbing solution conductivity dropped from 5000 to 150 µS/cm followed by an increase to the maximum or peak value. In the second run, using the same solution, the conductivity started by fast increase to a maximum value depending on the stage followed by gradual decrease towards the end of the incineration cycled time. The last run behaved the same with conductivity reaching a higher peak (480 µS/cm) compared to the first two peaks, which were between 420 and 450 µS/cm. Therefore, the profiles of scrubbing solution conductivity with time, are similar between consecutive runs and between the two stages, with exception of peak values and time to reach the peak value.

Comparison of conductivity profiles during incineration process

After initial scrubbing operation of 4 minutes, the scrubbing solution conductivity increases towards the peak value as stated above, location of which depends on solution inlet flow rate, R_L, and also on the characteristics of the solution (that is whether fresh, re-used or stored for use next day), and on the stage number. Figure 15 compares the scrubbing solution conductivity profiles beyond 4 minutes of scrubbing operation. The profiles can be characterized by peak value and location or time to reach the peak value, differences between stages, speed of decrease in conductivity after reaching the peak, which differ between stages and R_L values. The differences between profilers can be attributed to liquid inlet flow rate, lime dosage, quality of lime, etc. Other causes of differences in the profiles can be attributed to flue gas flow rate, combustion temperature, pressure, air flow rate, and combustion efficiency.

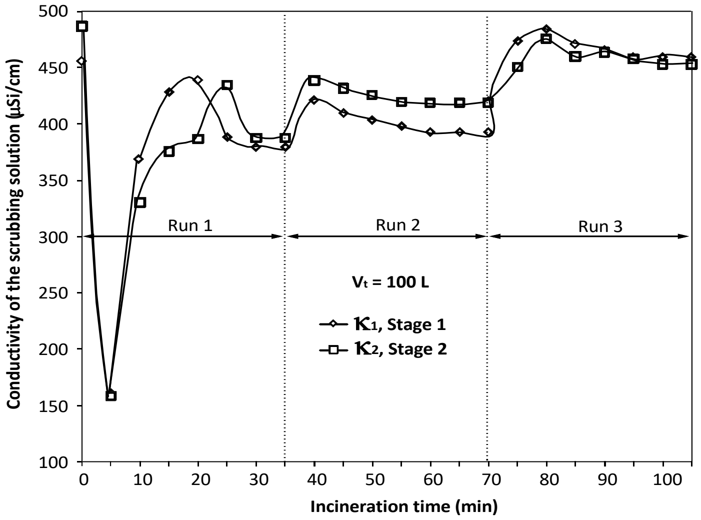

Figure 14: Variation of scrubbing solution conductivity with incineration cycle time for the multi-stage wet scrubber.

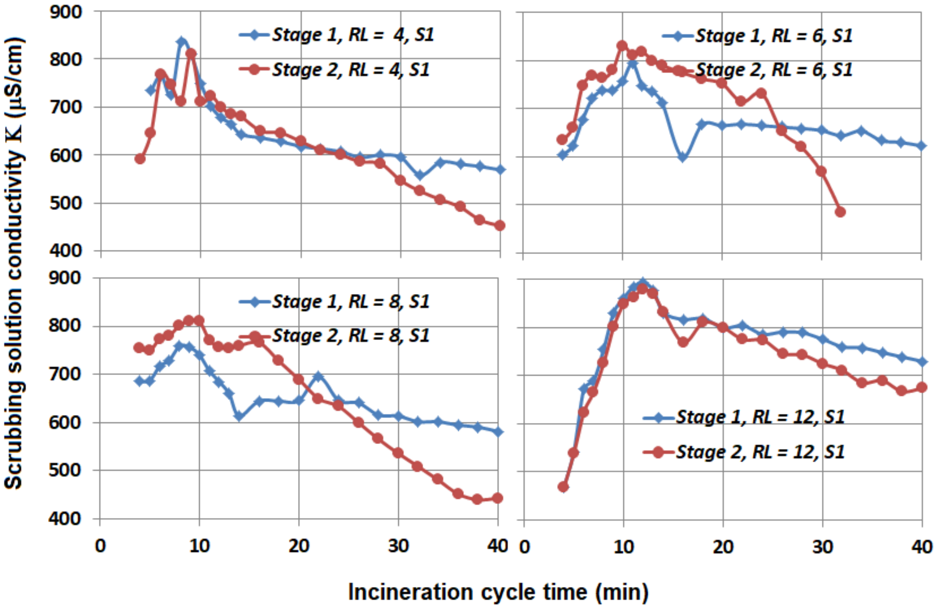

Figure 15: Scrubbing solution conductivity profiles for the multi-stage wet scrubber during incineration process.

CONCLUSION

Based on the results, it can be concluded that the pH of the scrubbing liquid for both scrubber Stages 1 and 2 decreased with increasing number of runs/operation time, showing that acid gases were being trapped by the solution, reacting chemically, and reducing the concentration or amount of alkali in the solution. The decrease in pH was faster when lime water was used as a scrubbing solution than when scrubbing liquid contained no lime, indicating that there is high scrubbing performance when lime is added. The decrease in pH ceases when the waste is completely burned in the chamber, indicating that no more acid gas is being generated. Large solution tank capacity allows the scrubber operation to be conducted at higher optimum liquid flow rates. The optimum liquid flow rates were established for different feed tank volumes. Both scrubber stages have the same performance when the solutions are prepared in the same way, leading to similar pH profiles, changes in pH and also equal values of pH^f, ΔpH^o and ΔpH^f. A correlation was observed between temperature and pH profiles. The conductivity of the scrubbing solution increased during scrubbing operation indicating that more ionic substances were being formed in the solution, indicating that the scrubber was trapping chemicals from the flue gas, rendering the latter less toxic.

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