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ABSTRACT

This work highlighted the determination of the best concentration profile for the operation of an absorber with potential to cut down combustion products emissions from the complete combustion reaction scheme of a combustion system waste stream. The proposed solvent concentration had a range of 1.84%-2.20% of caustic entrainment, therefore further increase on the solvent concentration above 2.20% is not feasible. Incremental changes of 0.06% were made to assess the optimal concentration required for best absorber performance. A process simulation software, ASPEN HYSYS 8.6, was utilized to simulate the emissions profile with PENG-ROBINSON as the Vapour-Liquid Equilibrium evaluation tool in the software. The study found the performance of the absorber improved with a corresponding increase in the concentration with 2.20% giving the most efficient removal rate of 61.59%, 26.5% and 85.2% for SO_2, CO_2 and NO_2, respectively. The study recommended that one veritable method of improving the performance of absorber systems is to increase the concentration of the alkali-based solvent to cut down on emissions from flue gas systems.

key words: **Absorber Performance, Solvent Concentration, Combustion Systems, Vapour-Liquid Equilibrium and Flue Gas Systems.**

1.0 INTRODUCTION

Combustion systems produce an array of products which is fed to the atmosphere. These releases cause delirious impacts on receptors if they are not controlled and mitigated. Air pollution control strategies have guaranteed that most combustion plants release a significantly lower emission compared to its original design by retrofitting accessory air pollution control (APC) facilities to cut down these emissions. It is important to note that the absorber have become common practice in combustion systems to remove gas emissions from combustion waste streams. The performance of the absorber and the absorption system is hinged on the principle of solvent and gaseous contact (Huertas *et al.,* 2015). The absorption process ensures the contact between the liquid solvent and the emissions to reach equilibrium (Abu-zahra, 2016). One major driving force of the mass movement of the gases into the liquid solvent is the concentration gradient. The mass movement of the emission stops only when the equilibrium of the concentration of the liquid phase and the gaseous phase is reached. Studies have repeatedly shown that there is corresponding increase in the removal of emission from waste stream of combustion system with solvent increase in concentration (Aroonwilas & Tontiwachwuthikul, 1997; Yu *et al*., 2011). The use of caustic concentration increases to remove acidic gases in an absorber system have proved successful in absorption studies (Mariana, *et al*., 2009; Nair & Selvi, 2014).

The increases is effected by the increase in the solvent mass per volume required for absorption. This higher increase has a corresponding effect higher gas/liquid interphase; with a possibility of more reactive contact sites. Tan *et al*. (2012) studied the effect of MEA concentration increase in the removal of CO_2 and discovered a profound increase of 96% from 91% CO_2 removal for a corresponding concentration increase from 18wt% to 30wt%. However, further concentration increase must be performed with cost profit in mind (Tan *et al.*, 2012). Huertas *et al*. (2015) also supports the principle of a better absorber performance with higher values of solvent concentration. Li *et al.* (2015) have reiterated the gains of increasing solvent concentration as a factor to improve the performance of the absorber. Furthermore, the study also showed a significant drop in energy consumption of the absorber unit during solvent regeneration and recovery schemes. Another equally beneficial advantage is the reduction in solvent circulation rate which leads to a significant reduction in the regeneration duty. Similarly to Tan *et al.* (2012), Li *et al.* (2015) have demonstrated that further concentration increases might increase operational cost due to the cost of the solvent as well as operational challenges caused by increased viscosity of the solvent. Raksajati *et al.* (2018) have attributed the use of smaller sizes of heat exchangers and absorbers to increases in the solvent concentration as this leads to considerable low regeneration energy.

The importance of increasing solvent concentration to improve absorber performance have been repeatedly demonstrated by various studies, however, further increases pose a performance declining process. Therefore, this study will attempt to show through emission simulation using ASPEN HYSYS to establish this fact in a complete combustion reaction scheme. The emission rate was evaluated from a boiler system operating to generate 120tonnes/h of steam for process utilization.

2.0: MATERIALS AND METHODS

The emission rate obtained by the evaluation of combustion products from a combustion system was stimulated using HYSYS 8.6. The composition of caustic utilised was constant at 1.84% while the temperature and flow rate of the solvent was maintained at 30°C and $5m^3/h$ respectively. The simulation package used in estimating Vapour-Liquid equilibrium, VLE data from the software was Peng-Robinson. Absorber performance with respect to variations to the concentration of the solvent was studied using incremental changes to ascertain improvement prospects. The simulation started at a composition of 1.96%, increasing incrementally at 0.06% up till 2.20%. Since the composition of 1.84% was utilised in the design, care was taken not to overshoot the economics of optimal operation as a result of cost of solvents which is a major contributor of increased solvent composition. The flue gas temperature was 181°C which was reduced to 120°C by the help of a cooler.

3.0: RESULTS AND DISCUSSION

The results generated from the simulation of the absorber performance with respect to the changes to the concentration of solvent were evaluated and highlighted in Table 1, Table 3, Table 5, Table 7 and Table 9. Vital parameters that were recorded during the simulation was also highlighted in Table 2, Table 4, Table 6, Table 8 and Table 10.

Table 1 illustrates the simulated results of the effects on the absorber performance at a caustic concentration of 1.96%.

Table 1: Compositional Variation of the Caustic at a Concentration of 0.0196

Compositional Mole Fraction	**Flue Gas**	**SOLVENT**	**Absorber Flue gas**	**Vapour**	**Liquid**
CO_2	0.946879	0	0.946879	0.69567	0.010045
SO_2	0.000416	0	0.000416	0.0004	0
H_2O	0.04812	0.9804	0.04812	0.30316	0.150592
NaOH	0	0.0196	0	0	0.839097
NO_2	0.004585	0	0.004585	0.00077	0.000267

At this solvent concentration, about 3.85% of SO_2 were removed from the combustion waste stream while only almost 27% of CO_2 were removed from the combustion waste stream. Furthermore, the results demonstrate that a significant 84.5% of NO_2 were equally removed from combustion waste stream.

Table 2 indicates the various parameters for variables used in the simulation studies.

Table 2: Material Balance Data at a solvent composition of 0.0196

	Unit	**Flue Gas**	**SOLVENT**	**Absorber Flue gas**	**Vapour**	**Liquid**
Vapour Fraction		1	0	1	1	0
Temperature	*C*	181	30	120	71.32011	92.80787
Pressure	*kPa*	101.3	101.325	101.3	101.3	121.59
Molar Flow	*kgmole/h*	749.8141	280	749.8141	1023.674	6.139936
Mass Flow	*kg/h*	32074.14	5157.479	32074.3	37006.26	225.5181
Liquid Volume Flow	*m^3/h*	38.63177	5.077023	38.63199	43.57337	0.135651

At a solvent concentration of 1.96%, the solvent temperature, pressure and flow rate was 120^{o}C, 101.3Kpa and 5m^3/h respectively. The flue gas however, was reduced from a temperature of 181^{o}C to a temperature of 120^{o}C by the deployment of a cooler. The absorber outlet had temperatures of 71^{o}C for the vapour outlet while the liquid outlet was about 93^{o}C. The flow rate of the absorber liquid outlet was 0.14m^3/h.

Table 3 illustrates the simulated results of the effects on the absorber performance at a caustic concentration of 2.02%.

Table 3: Compositional Variation of the caustic at a concentration of 0.0202

Compositional Mole Fraction	Flue Gas	SOLVENT	Absorber Flue gas	Vapour	Liquid
CO_2	0.946879	0	0.946879	0.69563	0.010045
SO_2	0.000416	0	0.000416	0.00038	0
H_2O	0.04812	0.9798	0.04812	0.30318	0.150592
NaOH	0	0.0202	0	0	0.839097
NO_2	0.004585	0	0.004585	0.00081	0.000267

At this solvent concentration, about 8.65% of SO_2 were removed from the combustion waste stream while only almost 27% of CO_2 were removed from the combustion waste stream. Furthermore, the results demonstrate that a significant 82.3% of NO_2 were equally removed from combustion waste stream.

Table 4 indicates the various parameters for variables used in the simulation studies at a solvent concentration of 2.02%.

Table 4: Material Balance Data at a solvent composition of 0.0202

	Flue Gas	SOLVENT	Absorber Flue gas	Vapour	Liquid
Vapour Fraction	1	0	1	1	0
Temperature	181	30	120	71.32011	92.80787
Pressure	101.3	101.325	101.3	101.3	121.59
Molar Flow	749.8141	280	749.8141	1023.674	6.139936

Mass Flow	32074.14	5157.479	32074.3	37006.26	225.5181
Liquid Volume Flow	38.63177	5.077023	38.63199	43.57337	0.135651

Table 5 illustrates the simulated results of the effects on the absorber performance at a caustic concentration of 2.08%.

Table 5: Compositional Variation of the caustic at a concentration of 0.0208

Compositional Mole Fraction	**Flue Gas**	**SOLVENT**	**Absorber Flue gas**	**Vapour**	**Liquid**
CO_2	0.946879	0	0.946879	0.69561	0.010045
SO_2	0.000416	0	0.000416	0.00028	0
H_2O	0.04812	0.9792	0.04812	0.3032	0.150592
NaOH	0	0.0208	0	0	0.839097
NO_2	0.004585	0	0.004585	0.00091	0.000267

At this solvent concentration, about 32.69% of SO_2 were removed from the combustion waste stream while only almost 27% of CO_2 were removed from the combustion waste stream. Furthermore, the results demonstrate that a significant 80.2% of NO_2 were equally removed from combustion waste stream.

Table 6 indicates the various parameters for variables used in the simulation studies. At a solvent concentration of 2.08%.

Table 6: Material Balance Data at a solvent composition of 0.0208

	Unit	Flue Gas	SOLVENT	Absorber Flue gas	Vapour	Liquid
Vapour Fraction		1	0	1	1	0
Temperature	C	181	30	120	71.32011	92.80787
Pressure	kPa	101.3	101.325	101.3	101.3	121.59
Molar Flow	kgmole/h	749.8141	280	749.8141	1023.674	6.139936
Mass Flow	kg/h	32074.14	5157.479	32074.3	37006.26	225.5181
Liquid Volume Flow	m^3/h	38.63177	5.077023	38.63199	43.57337	0.135651

Table 7 illustrates the simulated results of the effects on the absorber performance at a caustic concentration of 2.14%.

Table 7: Compositional Variation of the caustic at a concentration of 0.0214

Compositional Mole Fraction	**Flue Gas**	**SOLVENT**	**Absorber Flue gas**	**Vapour**	**Liquid**
CO_2	0.946879	0	0.946879	0.69558	0.010045
SO_2	0.000416	0	0.000416	0.00031	0
H_2O	0.04812	0.9786	0.04812	0.3034	0.150592
NaOH	0	0.0214	0	0	0.839097
NO_2	0.004585	0	0.004585	0.00071	0.000267

At this solvent concentration, about 25.5% of SO_2 were removed from the combustion waste stream while only almost 27% of CO_2 were removed from the combustion waste stream.

Furthermore, the results demonstrate that a significant 84.5% of NO_2 were equally removed from combustion waste stream.

Table 8 indicates the various parameters for variables used in the simulation studies. At a solvent concentration of 2.14%.

Table 8: Material Balance Data at a solvent composition of 0.0214

	Unit	**Flue Gas**	**SOLVENT**	**Absorber Flue gas**	**Vapour**	**Liquid**
Vapour Fraction		1	0	1	1	0
Temperature	*C*	181	30	120	71.32011	92.80787
Pressure	*kPa*	101.3	101.325	101.3	101.3	121.59
Molar Flow	*kgmole/h*	749.8141	280	749.8141	1023.674	6.139936
Mass Flow	*kg/h*	32074.14	5157.479	32074.3	37006.26	225.5181
Liquid Volume Flow	m^3/h	38.63177	5.077023	38.63199	43.57337	0.135651

Table 9 illustrates the simulated results of the effects on the absorber performance at a caustic concentration of 2.20%.

Table 9: Compositional Variation of the caustic at a concentration of 0.0220

Compositional Mole Fraction	**Flue Gas**	**SOLVENT**	**Absorber Flue gas**	**Vapour**	**Liquid**
CO_2	0.946879	0	0.946879	0.69556	0.010045
SO_2	0.000416	0	0.000416	0.00016	0

H_2O	0.04812	0.978	0.04812	0.3036	0.150592
NaOH	0	0.022	0	0	0.839097
NO_2	0.004585	0	0.004585	0.00068	0.000267

At this solvent concentration, about 61.53% of SO_2 were removed from the combustion waste stream while only almost 27% of CO_2 were removed from the combustion waste stream. Furthermore, the results demonstrate that a significant 85.2% of NO_2 were equally removed from combustion waste stream.

Table 10 indicates the various parameters for variables used in the simulation studies. At a solvent concentration of 2.20%.

Table 10: Material Balance Data at a solvent composition of 0.0220

	Unit	**Flue Gas**	**SOLVENT**	**Absorber Flue gas**	**Vapour**	**Liquid**
Vapour Fraction		1	0	1	1	0
Temperature	*C*	181	30	120	71.32011	92.80787
Pressure	*kPa*	101.3	101.325	101.3	101.3	121.59
Molar Flow	*kgmole/h*	749.8141	280	749.8141	1023.674	6.139936
Mass Flow	*kg/h*	32074.14	5157.479	32074.3	37006.26	225.5181
Liquid Volume Flow	*m^3/h*	38.63177	5.077023	38.63199	43.57337	0.135651

At a solvent concentration of 1.96%, the solvent temperature, pressure and flow rate was 120^{o}C, 101.3Kpa and 5m^3/h respectively. The flue gas however, was reduced from a temperature of 181^{o}C to a temperature of 120^{o}C by the deployment of a cooler. The absorber outlet had temperatures of 71^{o}C for the vapour outlet while the liquid outlet was about 93^{o}C. The flow rate of the absorber liquid outlet was 0.14m^3/h. These results were similar with the parameters obtained from the simulation at a concentration of 1.96%, 2.02%, 2.08% and 2.14% reported in Table 1, Table 2, Table 4, Table 6 and Table 8 respectively.

Table 11 shows the summary of the effects of the different solvent compositional variations with respect to the performance of the absorber. It clearly demonstrates the removal efficiency of the absorber with compositional increases.

Table 11: Summary of the effect of Compositional Variation of the Solvent on Absorber Performance

Solvent Composition	% Reduction SO_2	% Reduction CO_2	% Reduction NO_2
0.0196	3.85	26.5	83.2
0.0202	8.65	26.5	82.3
0.0208	32.69	26.5	80.2
0.0214	25.5	26.5	84.5
0.0220	61.53	26.5	85.2

As the composition changes gradually from 0.0196 to 0.0220, the percentage reduction of SO_2 changes from 3.85% to a significant 61.53%. The percentage reduction of CO_2 as well as that of NO_2 were not profound, however, an average of 83% reduction was recorded for NO_2 which clearly shows a better removal efficiency for NO_2.

The objective of the study was rooted in the overall removal of SO_2 from the exhaust channel of the combustion chamber. The study was limited by the availability of higher compositions hence the simulation studies was terminated at the composition of 0.0220.

Figure 1 demonstrates a graphical picture of the compositional variations of the solvent with respect to the removal of SO_2, CO_2 and NO_2 from the exhaust stream of a boiler combustion system. The figure also illustrates the linear trend of the removal capability of the absorber of SO_2 in the stream.

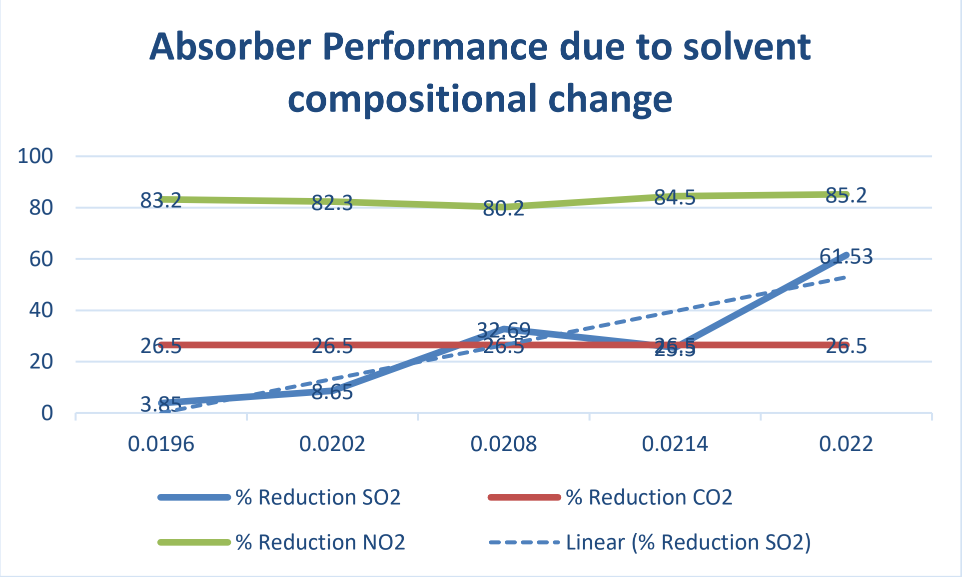

Figure 1: Compositional changes showing the trend of the removal efficiency

The trend line depicted a gradual increase in the caustic composition which presented a corresponding increase in the percentage reduction of SO_2. This clearly indicates that compositional increase in absorber solvents leads to increased performance level of the absorber.

4.0: CONCLUSIONS

Absorption process entails the use of a solvent to remove air pollutants from the waste stream of combustion processes. Alkali solvents used as absorption solvents is common within power generation industries. In the design and development of a retrofitted absorber system that has the potential to cut down emissions, deliberate efforts must be put forth to determine the concentration of the solvent required to increase the performance of the absorber. One vital parameter that affects performance of the absorber is solvent concentration. Concentration here refers to the amount of liquid volume or gaseous within a bulk volume (Fuentes-Arderiu, 2013)

Several studies have identified the increase in the concentration of the alkaline solvent as a basis for better performance of the absorber. This is owing to the fact that absorption process is a content process between the solvent liquid and the flue gas. The surface area of contact is increased by the corresponding increase in the solvent concentration.

However, further increase may hinder the performance in the absorber because of flooding and handling challenges. There is also the cost factor that needs to be balanced to ensure that the operation of the absorber is sustained and operational cost reduced considerably. It is on the premise of this specification of solvent composition that this work have varied composition of the solvent gradually to demonstrate concentration variations as a potent factor in increasing absorber performance.

The study noted a progressive improvement in the removal efficiency of the absorber with increases in solvent concentration, at a solvent composition of 1.96%, the removal rate percentages were 3.85% for SO_2, 21.2% for CO_2 and 83.2% for NO_2. The composition was gradually increased and the performance peaked at a solvent composition of 2.20% where the emission removal percentages for SO_2, CO_2 and NO_2 were 61.53%, 26.5% and 85.2% respectively.

Further increases were possible, however, the study stopped at 2.20% because of the availability of caustic solvent bulk volume needed for operation had a limitation for the caustic composition.

It is recommended that the performance of absorbers must be considered with the solvent concentration in mind in order to develop a system for optimal performance. Other parameters of solvent flow rate, solvent pH, absorber temperature, flue gas flow rate, etc. contribute a great deal also in the overall performance of the absorber as a potent tool for absorption process systems.

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