

Modelling Carbon Monoxide Capture through Post-Combustion Using Saw Dust Ash Leachate

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Abstract—It has become expedient to solve the prominent issues of carbon monoxide hazards by promptly capturing it at the source. This paper presents the analysis of carbon monoxide capture experimental results obtained with the use of saw dust ash leachate as the sorbents for the post-combustion capture of carbon monoxide from exhaust of Yamaha EF1000. The Yamaha EF1000 was appropriately connected to a laboratory scale glass absorber column for the counter current flow of the flue gas with the sorbent. Modelling and optimization of the process were carried out using Design Expert software version 10, with concentration of sorbents, process time and sorbent flow rate as the process variables. Quadratic model was obtained as the best model for the capture process, with the carbon monoxide composition of the exit flue gas as response. For the ash leachate, response value of 3.557% as optimum, at sorbent concentration of 21.795g/L, process time of 9.997mins and sorbent flow rate of 200.278cm³/min, respectively were achieved. From the results obtained, saw dust ash leachate effectively captured CO.

Keywords— Modelling, optimization, carbon monoxide capture, flue gas, saw dust ash.

I. INTRODUCTION

There is no question that carbon monoxide is a pollutant with potential to harm all living things. But does CO also affect earth's climate? This will also be unravelled in the research. Unlike carbon dioxide, a compound that contains the same atoms as carbon monoxide is not known as a direct contributor to climate change. It does, however, play a role in this area and such roles can be investigated with the results of the sequestration.

Global warming is the increase in the average temperature of the earth. This effect is caused by anthropogenic greenhouse gases released to the atmosphere. The control of these greenhouse gases is arguably the most challenging environmental policy issue facing most countries. An approach that is gaining widespread interest is to control carbon oxides emissions by capturing them from fossil fuels, to continue to be used without contributing significantly to greenhouse warming.

Many researchers are aiming to develop new solvent technologies to improve the efficiency of the carbon oxides removal. Process model, simulation and evaluation are essential items to maximize the absorption process performance. Several researchers have modelled and studied the MEA absorption process (Abu-Zahra *et al.*, 2007), and most of their conclusions focused on reducing the thermal energy requirement to reduce the overall process expenses. This high-energy requirement makes the capture process

energy intensive and costly considering the cost of procuring even the MEA. Therefore, it is important to study other alternative solvent to achieving the capture. Also as part of an effort to study climate change, effects of carbon monoxide as a pollutant to atmosphere, have been given attention.

The control of greenhouse gases is arguably the most challenging environmental policy issue facing most countries today. The development of new technologies for the management of the aforementioned challenge is the key drive for this research, and this is even more imperative as there is now need for a shift from the conventional and commonly used chemicals to locally sourced waste materials, to accomplish the purpose. In this regard, sawdust ash is considered to be of advantage, since the problem of waste materials disposal have continually posed pollution and health problems to the public, and have been of great concern to researchers. To making sawdust ash useful, this research work concentrates on the viability of using sawdust ash (SDA) leachate for the capture of carbon monoxide from flue gas and comparing the results with that achieved with the use of conventional chemicals.

II. MATERIALS AND METHODS

To produce saw dust ash of required particle size and quality, 2kg of saw dust sample was weighed and dried in an electric oven at 130⁰C for 2 hours. The sample was later charred using a low flame in a fume cupboard until it has ceased smoking. The charred sample which was in crucibles were placed in a cold muffle oven (electric furnace) and the temperature was set at 550⁰C. The sample was treated for 12 hours at 550⁰C. After that, the muffle furnace was turned off and allowed to cool to at about 150⁰C before it was opened. Safety tongs was used to transfer the crucibles containing the sample to a desiccator with porcelain plate and desiccant. The crucibles were covered and the desiccator was closed. The crucibles were allowed to cool prior to weighing. Finally, the saw dust ash was screened through a mesh size of 0.1mm to obtain particulates suitable for the ash leachate preparations.

The various concentrations (in g/L) of the ash leachates were then prepared by weighing required quantities of the saw dust ash and dissolving same accordingly in predetermined volumes of deionized water to obtain appropriate ash leachate concentrations, for the carbon capture (from flue gas of Yamaha EF1000) experimental runs.

2.1 Materials

a. Reagents Used

- Saw dust ash
- Distilled and De-ionized water
- 0.1M NaOH Solution
- Phenolphthalein indicator

b. Apparatus/Equipment Used

- Laboratory scale absorber column set up
- Dosing pump (Model: JM 15.77/4.2)
- Yamaha (Model: EF1000)
- Gas analyzer (Model: Ambro 2000)
- Analytical balance (Model: Adventurer Pro A35, Make: OHAUS)

2.2 Methods

a) CO capture with SDA Leachate

Seventeen (17) sets of SDA leachate were prepared to concentrations of 1.25, 11.88 and 22.50g/L, depending on the run concentration as suggested by the 3-level experimental design. The prepared sequestrants were made available for the sequestration experiments. The experimental glass absorber was mounted on a table, and the gas and liquid inlets and outlets were connected appropriately. The dosing pump (for the sequestrant transport) was then connected accordingly and the equipment connected to a power source and set to the required % stroke value (depending on the flow rate of the experimental run to be carried out), for the required optimal flow. Yamaha EF1000 was put on, and after about two minutes the exhaust gas was analyzed for the CO composition, then the flue gas exhaust was connected through to the absorber column gas inlet pipe. After this, the dosing pump was switched on for the sequestrant circulation through the column, and in a counter current flow with that of the entry flue gas. This CO capture process was monitored for a period of 5 - 10 minutes (depending on the experimental run performed), after which the gas analyzer Ambro 2000 was used to check for the CO composition of the exiting gas (lean gas) from the column.

b) Determination of CO composition in flue gas

The Gas Analyzer (Model: Ambro 2000) was put on and allowed to boot for about five minutes, after which the equipment was set on the program for the parameter to be tested. The equipment gas sensor was brought to the gas exit point of the absorber set up, in order to detect the CO composition of the flue gas. Also the CO composition of the flue gas coming out directly from Yamaha EF1000 exhaust was determined and recorded.

c) Optimization

Design Expert software was used in the Regression Statistical Analysis of the results for the SDA leachate absorption processes. The experimental data were gathered in the required format for the statistical study, and the collated data were used in the analysis to generate the necessary statistical parameters useful in the statistical model development and optimization.

The process variables (X) used for the computer analysis are as follows:

X₁ = Concentration of SDA leachate (g/L)

X₂ = Sequestration time (mins)

X₃ = Flow rate of sequestrant (cm³/min)

While the response variable (Y) for the computer analysis is:

Y = CO composition of exit flue gas (%)

For the response variable; the optimum process conditions are the X₁, X₂, X₃ values that yield the optimum (minimum) Y value.

d) Experimental Design

TABLE 1. Experimental design code and boundary/limit for the factors (Independent variables)

S/N	Variable	Code (X)	Boundary	
			Lower	Upper
1	Concentration of SDA leachate (g/L)	X ₁	1.25	22.5
2	Sequestration time (mins)	X ₂	5	10
3	Flow rate of sequestrant (cm ³ /min)	X ₃	200	250

III. RESULTS AND DISCUSSION

3.1 Characterization of the Saw Dust Ash/Leachate

TABLE 2. Result for the physical parameters of SDA

S/N	Parameter	Trial 1	Trial 2	Trial 3	Trial 4	Average
1	pH	10.12	10.14	10.17	10.18	10.15
2	Conductivity, $\mu\text{s}/\text{cm}$	1920	1900	1960	1880	1915
3	Total Dissolved Solids, mg/l	1248	1234	1274	1222	1245
4	Salinity, mg/l	115.20	82.29	65.83	98.75	90.52
5	Total organic matter, %	99.24	99.17	99.17	99.19	99.19
6	Moisture content, %	50.362	51.080	50.792	50.934	50.792
7	Ash content, %	75.5	82.9	83.3	81.0	80.7

In Table 2, the compositional analysis of the saw dust ash/leachate used for the absorption experiments has revealed that the physical parameters analyzed produced results which agree with most of the literature findings and as expected for effectiveness for the purpose. The leachate is seen to be alkaline in nature, with a very high conductivity value of 1915 $\mu\text{s}/\text{cm}$ on the average. The total dissolved solids produced a high result as expected and the salinity was also high. The saw dust ash had a total organic matter content of over 99% with moisture content of about 50%.

In line with the alkaline result obtained for the SDA, Huang *et al.* (1992) asserted wood ash as a soil additive and liming agent. Ohno (1992) noted that acidity of soil can be neutralized by addition of wood ash, and phosphorus and potassium nutrients could be augmented by the application equally.

TABLE 3. Result for the particulate analysis of SDA

S/N	Parameter	Trial 1	Trial 2	Trial 3	Trial 4	Average
1	Bulk density, g/cm^3	0.10018	0.10014	0.10018	0.10019	0.10017
2	Pore volume, cm^3	0.3476	0.3468	0.3477	0.3469	0.3472
3	Porosity	0.01738	0.01734	0.01740	0.01740	0.01738

For the particulate analysis, from Table 3, the bulk density is seen to be as low as 0.1g/cm³ with pore volume of

approximately 0.35cm^3 and porosity value of 0.017. Someshwar (1996) indicated that depending on the method with which wood ash is obtained, it is usually found to have a bulk density of ± 0.1 and porosity almost as low as 0.02.

TABLE 4. Result for the mineral content analysis of SDA

S/N	Parameter	Trial 1	Trial 2	Trial 3	Trial 4	Average
1	Chloride, mg/kg Cl	63.77	45.55	36.44	54.66	50.105
2	Nitrate, mg/kg NO ₃	10.60	21.71	15.60	12.00	14.98
3	Nitrate-nitrogen, mg/kg NO ₃ -N	2.40	4.90	3.60	2.70	3.40
4	Phosphate, mg/kg PO ₄ ³⁻	2.30	1.90	1.30	1.50	1.75
5	Phosphorus, mg/kg P	0.70	0.60	0.40	0.50	0.55
6	Sulphate, mg/kg SO ₄ ²⁻	5.00	5.00	5.00	5.00	5.00
7	Sodium, mg/kg Na	5.05	5.10	5.15	6.00	5.33
8	Potassium, ppm K	3.00	3.10	3.30	4.20	3.40
9	Calcium, mg/kg Ca	484.97	432.86	476.95	501.00	473.95
10	Magnesium, mg/kg Mg	44.506	48.883	44.749	41.344	44.871
11	Iron, mg/kg Fe	0.20	0.22	0.14	0.17	0.18
12	Copper, mg/l Cu	3.62	3.22	3.81	3.29	3.49
13	Lead, mg/l Pb	0.132	0.086	0.100	0.626	0.236
14	Manganese, mg/l Mn	0.50	0.40	0.80	0.30	0.50
15	Chromium, mg/l Cr	0.041	0.026	0.030	0.036	0.033
16	Zinc, mg/l Zn	28.68	28.54	27.91	28.04	28.29

As seen in Table 4, the mineral content analysis showed good content for chloride and nitrate, and low contents as obtained for the phosphates and sulphate values. Among the light metals, calcium was found to be more available in the saw dust ash with value over 400mg/l. The heavy metals as expected are in trace amounts, except for zinc which was as high as 28mg/l. Most of the parameter values obtained in the SDA characterization are found to be about similar values as outlined by Etiegni and Campbell (1991).

However, Misra *et al.* (1993) noted wood ash composition to be a function of the furnace temperature during the processing. It therefore indicates that for the furnace ash processing temperature used, these values obtained could be slightly varied depending on the ashing (furnace) temperature used.

3.2 Results for CO Capture using SDA Leachate

In the result Table 5 for the experimental runs, sorbent concentrations within the range of 1.25g/L and 22.50g/L were used. This was due to the ash dissolution difficulty encountered in preparing SDA leachate concentrations above 22.5g/L.

Again for the preliminary runs set up, after some initial trials have been carried out, the optimal sequestrant flow rate were found to be within the range of 200cm³/min to 250cm³/min, for the successful operation of the laboratory scale glass absorber without flooding. And the pump settings

at which the aforementioned optimal liquid flow were established were 30%, 40% and 50% strokes, which were subsequently adopted in the design of experiments.

TABLE 5. Result for CO capture using SDA leachate as absorber liquid (sorbent)

S/N	Run	Block	X ₁ (g/L)	X ₂ (mins)	X ₃ (cm ³ /min)	Y (%)
1	16	Block 1	1.25	5.00	225.00	6.48
2	12	Block 1	22.50	5.00	225.00	5.72
3	2	Block 1	1.25	10.00	225.00	4.83
4	6	Block 1	22.50	10.00	225.00	4.89
5	4	Block 1	1.25	7.50	200.00	5.15
6	1	Block 1	22.50	7.50	200.00	4.88
7	17	Block 1	1.25	7.50	250.00	5.00
8	10	Block 1	22.50	7.50	250.00	4.47
9	5	Block 1	11.875	5.00	200.00	6.78
10	15	Block 1	11.875	10.00	200.00	3.64
11	14	Block 1	11.875	5.00	250.00	4.92
12	9	Block 1	11.875	10.00	250.00	5.06
13	7	Block 1	11.875	7.50	225.00	5.68
14	3	Block 1	11.875	7.50	225.00	5.60
15	8	Block 1	11.875	7.50	225.00	5.70
16	13	Block 1	11.875	7.50	225.00	6.01
17	11	Block 1	11.875	7.50	225.00	5.69

Box bekhen design for three factors and three levels was used in the design of experiments for the laboratory experimental runs, producing seventeen (17) experimental runs. The factors (independent variables; X₁, X₂ and X₃) were taken to be the concentration of sequestrant (g/L), sequestration time (mins) and flow rate of sequestrant (cm³/min) respectively, while the response (Y) was taken to be the CO compositions of the exiting flue gas from the absorber column. For the factors (with box bekhen design), experimental design data points of 1.25, 11.88 and 22.50g/L were used for the concentration of the sequestrant, data points of 5, 7.5 and 10mins for the sequestration time, and for the flow rate of sequestrant, 200cm³/min, 225cm³/min and 250cm³/min were used.

The CO compositions of the flue gas from the absorber column when the SDA leachate was used as sequestrant were found to be within the values of 3.64% and 6.78%. However, the CO composition of the flue gas exiting directly from the Yamaha EF1000 was measured by the Ambro 2000 Gas Analyzer, and found to have a value of 8.2%. According to Gale (2002), domestic power generating sets could form part of the well-known potential carbon oxides emission sources from which it is a possibility to capture and store carbon. Gielen and Moriguchi (2003) reiterated that absorption (or scrubbing) remains one of the effective approaches to carbon capture from flue gases of both large and medium scale industrial plants.

Imai (2003) is of the view that better and more advanced solvents for carbon capture from flue gas will in the future be developed from biological sources, which is in line with the essence of the investigation in this work, by comparing the capture performance of SDA leachate with that of the conventionally used MEA for the purpose.

Mimura *et al.* (1995) showed immense concern through their research on energy saving technology for flue gas carbon oxides recovery and steam system in power plant. Their effort

was geared towards minimizing the energy requirement for the capture process which happens to be a major advantage of the quest for this work.

Moser et al. (2009) worked on enabling post combustion capture optimization with the pilot plant project at Niederaussem. Even though they used conventional liquid for capture, their optimization approach involved setting out process factors and performing the capture at the various defined factor combinations, which is an analogue of what has been done in this work.

Rao and Rubin (2002) after working on a technical, economic and environmental assessment of amine-based carbon capture technology for power plant greenhouse gas control, agree to the fact that the exercise with the chemical based liquid even though technically effective and environmental assessment commendable, the economics of the process remains a factor of concern. This present quest to ascertain the replaceability of conventional chemical liquids with locally (prepared) sourced alternatives seeks to address that.

From the results, the effect of each of the factors were better understood when statistical analysis were done based on the results with which statistical models were developed and response surface methodology carried out for the purpose of optimizing the capture process conditions under investigation in this work. These and their respective discussions are outlined in the subsequent section 3.3 that follows.

3.3 Results for the Statistical Analysis, Modelling and Optimization

TABLE 6. ANOVA for Reduced Response Surface Quadratic model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	283.27	7	40.47	38.23	< 0.0001	significant
A-Conc. of SDA leachate	73.8	1	73.8	69.71	< 0.0001	
B-Sequestration time	17.78	1	17.78	16.79	0.0027	
C-Flowrate of sequestrant	8.6	1	8.6	8.12	0.0191	
AB	83.24	1	83.24	78.63	< 0.0001	
AC	7.31	1	7.31	6.9	0.0275	
A ²	5.57	1	5.57	5.26	0.0476	
C ²	87.47	1	87.47	82.62	< 0.0001	
Residual	9.53	9	1.06			
Lack of Fit	5.68	5	1.14	1.18	0.4486	not significant
Pure Error	3.85	4	0.96			
Cor Total	292.79	16				

Std. Dev.	1.03	R-Squared	0.9675
Mean	26.75	Adj R-Squared	0.9422
C.V. %	3.85	Pred R-Squared	0.8611
PRESS	40.66	Adeq Precision	21.533
-2 Log Likelihood	38.4	BIC	61.07
		AICc	72.4

The Model is significant with an F-value of 38.23. And there is only a 0.01% chance that an F-value this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, AB, AC, A², C² are all significant model terms. Values greater than

0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve the model.

The "Lack of Fit F-value" of 1.18 implies the Lack of Fit is not significant relative to the pure error. There is a 44.86% chance that a "Lack of Fit F-value" this large could occur due to noise. While non-significant lack of fit is good because it means the model would fit.

The F-values of the independent variables (sequestrant concentration, sequestration time, flow rate of sequestrant) were estimated as 69.71, 16.79, and 8.12 respectively, showing that the single effects of the independent variables are significantly high on the response (CO composition of the exit flue gas stream). The CV called coefficient of variation which is defined as the ratio of the standard deviation of estimate to the mean value of the observed response is independent of the unit. It is also a measure of reproducibility and repeatability of the models (Chen *et al.*, 2010; Chen *et al.*, 2011). The calculations indicated the CV value of 3.85% which illustrated that the model can be considered reasonably reproducible (because its CV was not greater than 10%), (Chen *et al.*, 2011). The signal to noise ratio which is given as the value of the adequacy precision is 21.533. This indicates that an adequate relationship of signal to noise ratio exists and model can be used to navigate the design space.

The selected model in terms of the coded and actual values is given in the equation below:

$$\text{CO composition of exit flue gas} = 5.729 - 0.685A - 0.187B - 0.125C + 0.205AB + 0.820AC - 0.241B^2 - 0.621C^2$$

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels of the factors are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

In terms of Actual values, the model terms are given by:
 CO composition of exit flue gas = - 18.68163 - 3.31765 * A - 0.024761 * B + 0.34395 * C + 0.00772 * A * B + 0.01312 * A * C - 0.00214 * B² - 0.000994 * C²

The equation in terms of actual factors can be used to make predictions about the response for given levels of each factor. Here, the levels are specified in the original units for each factor. This equation should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor and the intercept is not at the centre of the design space.

The response values obtained by inserting the independent values are the predicted values of the model. These values are compared to the actual and experimental values. The result of this comparison is shown in figure 1.

From figures 1, it can be seen that the actual values were relatively distributed near to the predicted value line showing that there is a good correlation between the actual values and the predicted values. This observation shows that the central composite design (CCD) is well fitted for the developed model and can be used to perform the optimisation for the process.

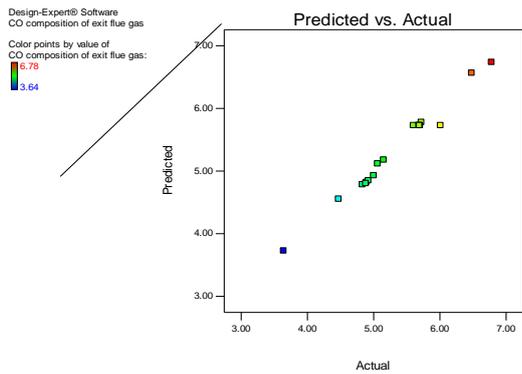


Fig. 1. Linear correlation between vs. actual values for effect of CO reduction using SDA leachate

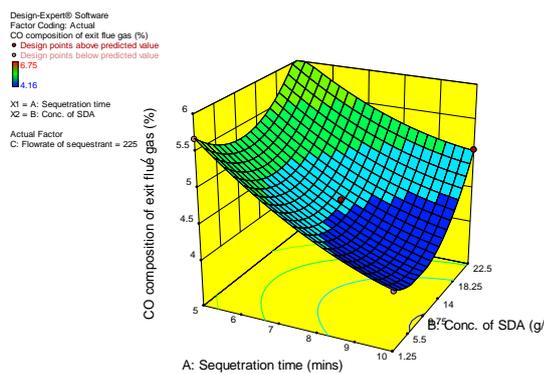


Fig. 2. Surface Response Plot (SDA Leachate) – Using Concentration of SDA Leachate (A, g/L) and Sequestration time (B, mins) as Factors, with 'CO Composition of Exit Flue Gas' as Response

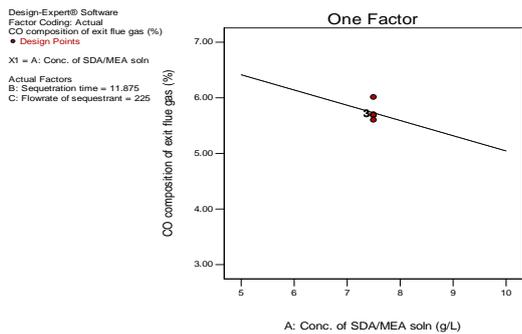


Fig. 3. One Factor plot of CO comp. against sequestration time

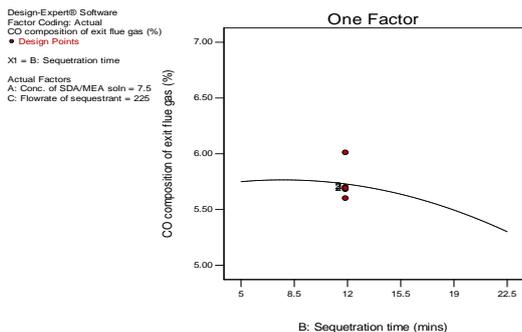


Fig. 4. One Factor plot of CO comp. against concentration of SDA Leachate

In order to visualize the relationship between the experimental variables and the response, and to study individual and interaction effects of the three factors consisting of the SDA leachate concentration, sequestration time, and flowrate of sequestrant, response surfaces and interaction plots were generated from the quadratic model, as shown in figures 2 - 4. These figures illustrate the response of different experimental variables and can be used to identify the major interactions between the variables.

Figures 2 to 4 show the 3D plot and its corresponding interactions for the effects of SDA leachate concentration on composition of CO in the exit flue gas stream. The graphs show that the least recorded value for CO in the exit streams occur between 16.8g/L and 11.6g/L SDA Leachate concentration, which is in accordance with the model. As the SDA leachate concentration is increased from 8.3g/L to 15.4g/L, the amount of CO in the exit stream steadily decreases from 5.56% to 5.24% as seen in figure 4. This is similar to the report of several researchers (Moser *et al.*, 2009) who agree that increase in sequestrant concentration results in decrease in carbon oxides composition of the exit flue gas stream. It is evident that the SDA leachate concentration has a significant effect on the response. Increasing the SDA leachate concentration beyond 18.5g/L at all levels of sequestration time results in the gradual increase of CO composition of the exit flue gas stream. As expected, the CO level decreased linearly with increase in sequestration time (figures 3). This effect is independent of the SDA leachate concentration as seen on the 3D plot of figure 2.

The effect of sequestrant flow rate and sequestration time on the CO composition of exit flue gas is shown on the 2D contour plot of figure 5.

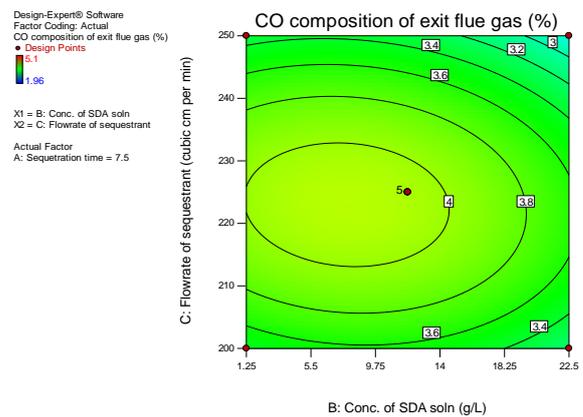


Fig. 5. 2D contour plot for the effect of sequestrant flowrate and conc. of SDA leachate on CO composition of exit flue gas

The capture was carried out at sequestration time of 7.5 minutes. The exit flue gas CO composition is seen to decrease steadily with increasing sequestrant flowrate from 200 - 225 cm³/min, where the lowest value of 3.6% CO is recorded. Beyond 225 cm³/min, the amount of CO captured in the exit stream begins to increase steadily with increasing sequestrant flowrate. This trend is observed for all values of SDA leachate concentrations. However, the lowest value of 3.6% for CO

composition of exit flue gas was recorded at sequestration time of 22.5g/L and 225 cm³/min flowrate. It is good to note that the decrease in the composition of exit flue gas with corresponding decrease in flowrate is as a result of an enhanced interaction created which further enhances the capture process.

Tables 7 and 8 below outline the constraints and solutions for the optimisation results of the capture with SDA leachate.

TABLE 7. Optimisation constraints values for factors and responses

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: Conc. of SDA leachate	is in range	1.25	22.5	1	1	3
B: Sequestration time	is in range	5	10	1	1	3
C: Flowrate of sequestrant	is in range	200	250	1	1	3
CO composition of exit flue gas	minimize	3.64	6.78	1	1	3

TABLE 8. Optimisation solutions values for factors and responses

Number	Conc. of SDA leachate	Sequestration time	Flowrate of sequestrant	CO composition of exit flue gas	Desirability
1	21.795	9.997	200.278	3.557	1 Selected
2	19.694	9.997	200.022	3.614	1
3	22.180	9.929	201.046	3.634	1
4	19.444	9.989	200.198	3.639	1
5	22.346	9.929	201.159	3.635	1
6	20.427	9.973	200.195	3.616	1
7	21.130	9.959	200.479	3.619	1
8	20.640	9.950	200.269	3.626	1

From table 8, the obtained and selected optimum values for the sequestration with SDA leachate have CO composition of exit flue gas value of 3.557% as optimum (i.e minimum), at sequestrant concentration of 21.795g/L, sequestration time of 9.997mins and sequestrant flow rate of 200.278cm³/min respectively.

IV. CONCLUSION

SDA leachate was established to be a better sequestrant for carbon monoxide capture. There was more decrease in the CO composition of the flue gas during carbon capture with SDA leachate. From the optimization results, about 65% reduction in flue gas carbon oxide contents have been achieved by SDA leachate.

The characterization of the SDA leachate showed that calcium ion was responsible for the sequestration due to its affinity for dissolved CO₂. Increase in the sequestrant concentration implies a reduction in the CO compositions of the flue gas. This was evident from the experimental results. However, concentration increase beyond 22.5g/L for SDA leachate proved impossible due to saw dust ash dissolution difficulty encountered in the process.

The decrease in the CO compositions of the flue gas at increased sequestrant flowrate (230 cm³/min - 250 cm³/min) can be attributed to the improved interaction of the dissolved carbon oxides with the ions in the leachate, due to increased flow.

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