VOL. 7, NO. 12, DECEMBER 2012 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

PERFORMANCE EVALUATION OF WET SCRUBBER SYSTEM FOR INDUSTRIAL AIR POLLUTION CONTROL

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ABSTRACT

The concentration of pollutants emitted from industrial production are generally toxic and hazardous, which can be a serious health risk to humans not limited to respiratory ailments (asthma, bronchitis, tuberculosis, etc) but also to the photosynthesis in plants. In this study, a pilot scrubber system for PM_{10} control has been designed using data obtained from cement industry. A model for the overall collection efficiency of counter current scrubber system and Langmuir's approximations were used to predict the performance of the system by considering droplet sizes of 500μm, 1000μm, 1500μm and 2000μm. The range of liquid to gas ratio recommended by the US Environmental Protection Agency (EPA) has been used to investigate the appropriate ratio for optimum performance of the system. Due to reversed flow in the Langmuir's approximation, negative collection efficiencies for the 1μm dust particle were obtained. For 5μm and 10μm dust particles, the maximum collection efficiencies were determined to be 99.988% and 100.000% at 500μm droplet size and 2.7 l/m^3 while the minimum was obtained to be 43.808% and 58.728% at 2000μm droplet size and 0.7 l/m^3. The predicted performance of the scrubber system was then validated using the World Health Organization (WHO) air quality standard for PM_{10}.

Keywords: industrial air pollution, wet scrubber system, performance evaluation, particulate matter.

1. INTRODUCTION

Increased public awareness posed by global warming has led to greater concern over the impact of anthropogenic emissions from industrial production. The dust particle emissions of $PM_{2.5}$, PM_{10} and TPM have been the subject of claims and there is urgent need to minimize the increase in the emission levels by reducing the mass load emitted from the exhaust stacks. Kabir and Madugu [1] and Huntzinger [2] indicated that the particle concentrations are generally toxic and hazardous which can be a serious health risk to humans not limited to respiratory ailments (asthma, bronchitis, tuberculosis, etc), but also to the photosynthesis in plants.

Tall stacks have traditionally been used to reduce ground level concentrations of air pollutants at minimum cost. Their effectiveness depends on height, velocity and temperature of the stack gases, and atmospheric conditions such as wind speed and direction, atmospheric stability, local topography and air quality as such serious environmental effects such as acid deposition and forest decline can occur in a sensitive receiving environments or remote locations (Ngala *et al.,* [3]).

This lead to the development of an alternative air pollution control systems; such as wet scrubber systems, gravity separators, centrifugal collectors, fabric filters (baghouse filters) and electrostatic precipitators (ESP) respectively. According to Frank and Nancy [4], wet scrubbers have important advantage when compared to other air pollution control devices. The device can handle large volume of gases, can collect dust particulates like flammable and explosive dusts, foundry dusts, cement dusts and can absorb gaseous pollutants, acid mists, furnace fumes. The most common type of wet scrubbers are the spray tower scrubber, packed bed scrubber, mechanically aided scrubber, venturi scrubber, etc.

But spray tower scrubber described in Figure-1 is the simplest and low-cost wet scrubber system in which water droplets are introduced at the top of an empty chamber through atomizing nozzles and fall freely at their terminal settling velocities counter-currently through the rising dust particle-gas stream. The dust particles are then separated from the gas stream and collected in a pool at the bottom of the chamber. A mist eliminator is usually placed at the top of the spray tower to remove both excess clean water droplets and dirty droplets which are very small and thus are carried upward by the gas flow.

Although spray tower scrubbers are commonly used to remove particulate matters ($PM_{2.5}$, PM_{10}, and PM_{TPM}) and other pollutants as presented in Makkinejad [5], Kim *et al*., [6], Rahimi *et al.* [7], Bingtao [8], Garba [9], Bozorgi *et al.* [10], Yetilmezsoy and Saral [11], Ngala *et al.* [3] and Passalacqua and Fox [12]. However, the exact mechanisms governing the optimum particle removal efficiency of the system in relation to the liquid droplet size and the liquid to gas ratio and the performance of the system based on the air quality standards are not fully described.

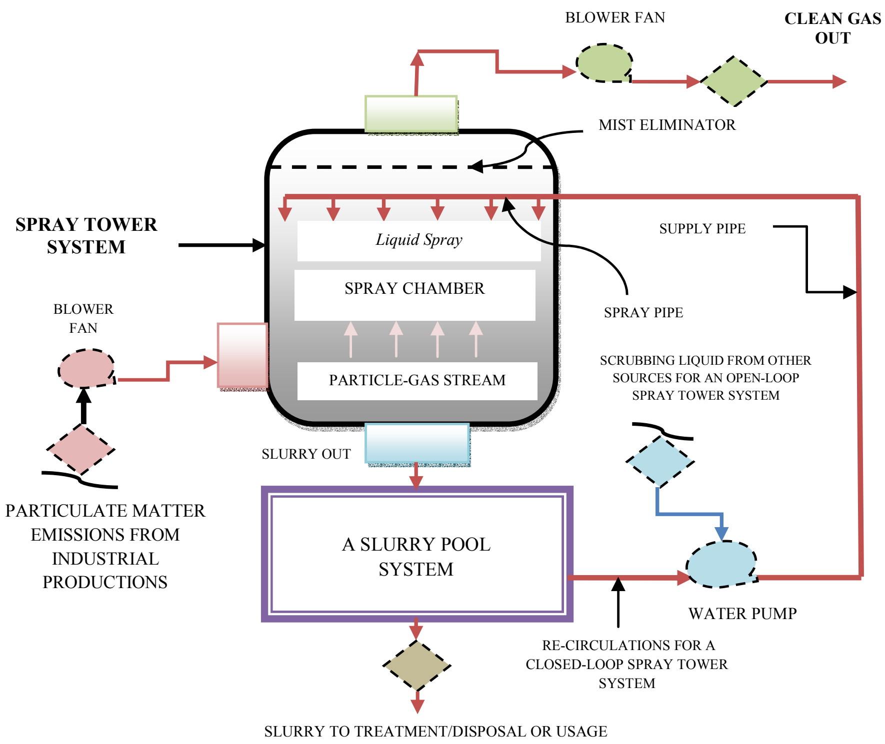

Figure 1: Wet Scrubbing Process in Spray Tower Scrubber System

The objective of the present study is to promote a better understanding of the sub-micron dust particle removal characteristics of spray tower scrubber system by analytically exploring the design of the system using data obtained from cement industry (Table-1), investigate the effect of droplet size and liquid to gas ratio on the removal efficiency of the scrubber system and evaluate the performance of the system using predicted values of the particle removal efficiency by considering the World Health Organizations' (WHO) air quality standard for PM_{10}.

Table-1. Exhaust particle-laden gas data.

Parameters	Specifications
Volume flow rate	29.13 m^3/s
Mass flow rate	33.08 kg/s
Gas density	0.82 kg/m^3
Dust burden (Concentration)	22, 859$\mu g/m^3$

Source: Ashaka Cement Company [13].

2. MATERIALS AND METHOD

The approach employed in this study was divided into design of the scrubber system and computations of the overall collection efficiency or the performance of the scrubber system using sets of theoretical models by considering impaction inertial separation mechanism as a function of the removal efficiency of the scrubber system for dust particle sizes of 1m, 5m and 10m (PM10) which reaches the upper parts of the human air ways and the lungs.

2.1. Design of the scrubber system

As indicated by Daniel and Paula [14], the waste gas flow rates are the most important parameters in designing a scrubber. For a steady flow involving a stream of specific fluid flowing through a cylindrical control volume of the scrubber system at sections 1 and 2;

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2 \qquad (1)$$

where, ρ_1 and ρ_2 are respective densities, A_1 and A_2 the cross sectional areas and V_1 and V_2 are the velocities, respectively. By using value for the mass flow rate in Table-1, exit velocity of 1.5m/s and substituting A_2 in (1), the diameter of the scrubber was determined to be 8.0m. The height of the spray tower system has been determined to be 16m by considering typical height to diameter ratio of cylindrical shell of approximately 2:1 in Cheremisinoff and Young [15].

2.1.1. Determination of the scrubber thickness

A carbon steel material was selected for the design of the scrubber wall, then from metals and materials Table, the modulus of elasticity, $E = 200.1 \times 10^9$ N/m^2. But the collapsing pressure in the scrubbing chamber is atmospheric, then $P_e = 101.3\times 10^3$ N/m^2. Assuming a factor of safety of 2, $P_e = 2 \times (101.3 \times 10^3) = 202.6 \times 10^3$ N/m^2. The numerical coefficient, $K = 50$ was adopted from Garba [8]. The thickness, *t* has been determined to be 0.0218m by using (2).

$$P_e = K\ E\left(\frac{t}{D}\right)^3 \tag{2}$$

2.1.2. Diameter of the pipe networks

Since the quantity of liquid needed for scrubbing, Q_L is 58.26 l/s (from the particle-laden gas flow rate in Table-1), considering the assumed liquid velocity of 3m/s, the diameter of the supply pipe was calculated to be 0.1572m using (3).

$$d_{\sup} = \left(\frac{4Q_L}{\pi\ V}\right)^{0.5} \tag{3}$$

Assuming the scrubber is divided into four sections, the diameter of each spray pipe in each section was determined by dividing the quantity of liquid needed for the scrubbing, Q_L by four so as to obtain quantity of water needed for scrubbing in each pipe, Q_{spray} = 0.0014565m^3/s. Using this value and substituting (4), the diameter of each spray pipe was obtained to be 0.0786m.

$$d_{spray} = \left(\frac{4Q_{spray}}{\pi V}\right) \tag{4}$$

2.1.3. Head losses within the pipe network

The total head loss, Δh_T was determined to be 408m using (5) and (6).

$$h_D = \frac{f\,LV^2}{D2g} \tag{5}$$

$$h_{LC} = k_C\frac{V_2^2}{2g} \tag{6}$$

2.1.4. Rate of energy gained by the scrubbing liquid

Using (8), the rate of energy gain was determined to be 233kw.

$$\Delta\dot{E} = \dot{m}\left(\frac{\Delta p}{\rho}\right) \tag{7}$$

where, *m* is the mass flow rate of the scrubbing liquid, Δp is the pressure drop obtained to be 4002kpa using (8), and ρ is the density of water at room temperature.

$$\Delta p = 0.0981\,\Delta h\ \gamma \tag{8}$$

where, γ is the specific gravity of water at room temperature and Δh is the total head loss.

2.1.5. Mechanical power delivered to the pump

When the pump operates at 85% efficiency during the wet scrubbing process, then an expression for the pumping efficiency described by (9) has been used to determine the mechanical power delivered to the pump as 274kw.

$$P_{pump} = \left(\frac{\Delta\dot{E}}{\eta_{pump}}\right) \tag{9}$$

Assuming the efficiency of the electric motor is 90%, then the electric power of the motor, $P_{electric}$ was obtained to be approximately, 305kw by using (10);

$$P_{electric} = \left(\frac{P_{pump}}{\eta_{motor}}\right) \tag{10}$$

2.1.6. Temperature rise of the scrubbing liquid

Using (11), the temperature rise was approximately determined to be 0.136^{o}C. This indicated that, the scrubbing liquid will experience a temperature rise of 0.136^{o}C due to mechanical inefficiency, which is very small. However, in an ideal situation, the temperature rise should be less since part of the heat generated will be transferred to the pump casing and to the surrounding air.

$$E_{loss} = m\ C_p\ \Delta T \tag{11}$$

2.2. Computations of the overall collection efficiency

The US Environmental Protection agency, EPA and National Association of Clean air Agencies, (USEPA and NACAA [16]), indicated that, mathematical models provides a means for predicting scrubber performance when empirical data and pilot scale data is not available. In this work, a mathematical model for the prediction of the overall collection efficiency of a countercurrent spray tower system was used to predict the removal efficiency which is also the performance of the proposed spray tower scrubber using input data from the design specifications (Z, D, d_{spray}), the system operating conditions (Q_L, Q_G, C_c, Re, η_{vis}, η_{pot}, η_I) and the gas-particle and droplet operating conditions (U_g, μ_g, ρ_g d_P, d_D, ρ_P, U_{td}), respectively. This model is given as;

$$\eta_{overall} = 1 - \exp\left\{-1.5\ \eta_I\ \alpha\ \beta\ \delta\ \right\} \tag{12}$$

where

$$\alpha = \frac{U_{td}}{U_{td} - U_g},\ \beta = \frac{Q_L}{Q_G},\ \delta = \frac{Z}{d_D}$$

$\frac{Q_L}{Q_G}$ = liquid to gas ratio,

N_z and N_0 are the outlet and inlet dust-particle (dust laden) concentrations in $\mu g/m^3$, U_{td} and U_g are the terminal settling velocity of water droplet and gas stream velocity while Z and η_I represents the spray tower height and impaction collection efficiency of single water droplet respectively. The model has been simplified as shown;

Using (12) above and the input variables, the removal efficiency was computed by considering the liquid to gas ratios recommended by US Environmental Protection Agency (USEPA, [17]): $\beta_1 = 0.7$ l/m^3, $\beta_2 = 1.7$ l/m^3 and $\beta_3 = 2.7$ l/m^3 and the results are presented in Tables 2, 3 and 4.

Steps for the determination of the input variables are presented below:

2.2.1. Calculations of impaction number

Impaction mechanism is prominently used in most studies relating to wet scrubber systems. A model for the determination of impaction number developed by Wark *et al*., [18] was used in this study. This is given by;

$$\psi = C_f \frac{\left(U_{td} - U_g\right) d_P^2 \rho_P}{18 \mu_g d_D} \tag{13}$$

where μ_g is the gas viscosity, ρ_P the particle density, d_P and d_D are the particle and droplet sizes while C_f is the Cunningham correction factor to allow for slip. The impaction number was calculated using (13) by considering the following variables:

2.2.1(a). Cunningham slip factor, C_f

This accounts for particles equal to or smaller than 1μm. (dp = 1μm). According to Abdel-Majid*, et al.*, [19]. This factor is assumed to be 1 when the particle is larger than 1μm.

Table-2. Overall collection efficiency for 1μm particle size.

α	δ	η_I	**β₁ = 0.7** (l/m³)		**β₂ = 1.7** (l/m³)		**β₃ = 2.7** (l/m³)	
			$\eta_{overall}$	$\eta_{overall}$ (%)	$\eta_{overall}$	η overall (%)	$\eta_{overall}$	$\eta_{overall}$ (%)
1.392	0.036	-43.19	-8.69967	-869.967	-248.120	-24812.0	-6397.26	-639726
1.168	0.018	-14.64	-0.38164	-38.164	-1.19259	-119.259	-2.47952	-247.95
1.120	0.012	-7.28	-0.10811	-10.811	-0.28313	-28.313	-0.48579	-48.579
1.098	0.009	-3.65	-0.03863	-3.863	-0.09641	-9.641	-0.15741	-15.741

Table-3. Overall collection efficiency for 5μm particle size.

α	δ	η_I	**β₁ = 0.7** (l/m³)		**β₂ = 1.7** (l/m³)		**β₃ = 2.7** (l/m³)	
			$\eta_{overall}$	$\eta_{overall}$ (%)	$\eta_{overall}$	$\eta_{overall}$ (%)	$\eta_{overall}$	$\eta_{overall}$ (%)
1.392	0.036	43.12	0.89657	89.657	0.99595	99.595	0.99984	99.984
1.168	0.018	55.51	0.70638	70.638	0.94901	94.901	0.99115	99.115
1.120	0.012	56.54	0.54969	54.969	0.85594	85.594	0.95392	95.392
1.098	0.009	55.55	0.43808	43.808	0.75336	75.336	0.89175	89.175

Table-4. Overall collection efficiency for 10μm particle size.

α	δ	η_I	**β₁ = 0.7** (l/m³)		**B₂ = 1.7** (l/m³)		**β₃ = 2.7** (l/m³)	
			$\eta_{overall}$	$\eta_{overall}$ (%)	$\eta_{overall}$	$\eta_{overall}$ (%)	$\eta_{overall}$	$\eta_{overall}$ (%)
1.392	0.036	75.80	0.98147	98.147	0.99994	99.994	1.00000	100.000
1.168	0.018	84.73	0.84598	84.598	0.98936	98.936	0.99926	99.926
1.120	0.012	85.83	0.70214	70.214	0.94721	94.721	0.99064	99.064
1.098	0.009	85.29	0.58728	58.728	0.88343	888.343	0.96708	96.708

2.2.1(b). The droplet size, d_D and terminal settling velocity of the liquid droplet, U_{td}

For optimum performance of spray tower system, the droplet size of water, d_D should be between 500 - 1000μm, (Garba, [8]). Hence, in this work a droplet size of 500μm, 1000μm, 1500μm and 2000 μm has been selected for the analysis of the scrubber system. Model for terminal settling velocity of water droplets was derived using one-dimensional motion of water droplet acted upon by gravity, drag and buoyant forces described by the equation:

$$U_{td} = \sqrt{\frac{4}{3}\frac{g d_D (\rho_D - \rho_g)}{C_D \rho_g}} \qquad (14)$$

Where ρ_D and ρ_g are liquid droplets and gas densities and C_D is the drag coefficient. However, using this model to determine the terminal settling velocity, U_{td} by iterations may not be enough as the drag coefficient chosen may be wrong. The most used and most reliable experimental measurements of terminal settling velocity of water droplets in the raindrop size ranges are those of Gunn and Kinzer [20]. The experimental measurement contains 33 data of size domains; 100μm ≤ d_D ≤ 5800μm.

In this study, the size domain for the experimental data was divided into 24 data for training and 9 data for validation and this was used to develop a curve fit model (Figure-2) for the prediction of the terminal settling velocity of the liquid droplets. The curve fit model was developed from smoothing spline fit having the best goodness of fit statistics; Sum of Squares due to Error (SSE) = 0.000267, Sum of Squares of the Regression (R-square) = 1, Adjusted R-square = 1 and Root Mean Square Error (RMSE) = 0.00542, respectively.

Using the curve fit model, the terminal settling velocities for the selected droplet sizes (500, 1000, 1500 and 2000μm) were estimated and the result is presented in Table-5.

Table-5. Water droplet sizes and their corresponding terminal velocities.

d_D (μm)	U_{td} (m/s)
500	2.06
1000	4.03
1500	5.42
2000	6.50

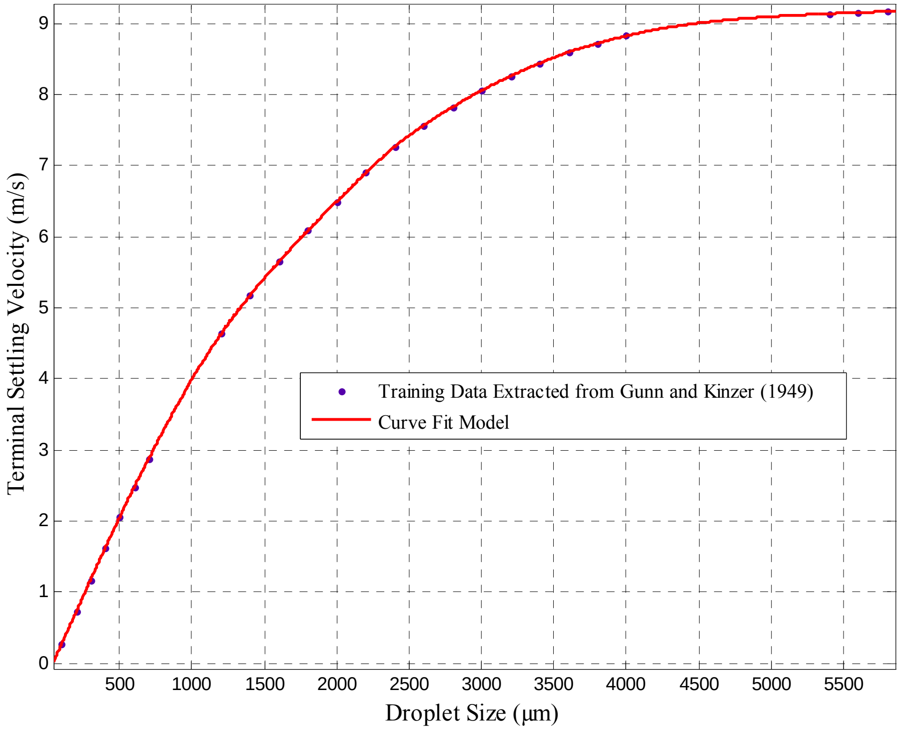

Figure-2. Experimental data and curve fit model for the terminal velocities.

2.2.1(c). Density of the cement particle, ρ_P

According to Ying [21], the solid particles are considered to be a rigid sphere; therefore their density is constant. From Portland cements test results, the density of the cement particle, ρ_P has been found to be 3120 kg/m^3 (Joao, [22]).

2.2.1(d). Dust-particle size, d_P

Although the particle sizes of dispersed cement dust ranges between 0.1-205μm (Ghosh, [23]). In this study, three mean diameters of 1μm, 5μm and 10μm were considered.

2.2.1(e). Gas density and viscosity

The gas was assumed to be air at 30^{0}C, therefore from table of properties of air in Yunus and John [24], the gas viscosity, μ_g is 1.86 ×10^{-5} kg/ms and the density, ρ_g is 1.18kg/m^3.

Having determined the required variables, the impaction numbers for the different particle and droplet sizes were calculated using (13) and the result is shown in Table-6.

Table-6. Impaction numbers for different particle sizes.

d_D (μm)	d_P = 1μm ψ_1	d_P = 5 μm ψ_2	d_P = 10 μm ψ_3
500	0.0384	0.960	3.840
1000	0.0376	0.939	3.756
1500	0.0337	0.842	3.367
2000	0.0303	0.757	3.029

2.2.2. Calculations of the impaction efficiency

Using the impaction number in (13), Licht, [25] described the impaction efficiency as;

$$\eta_I = \left[\frac{\psi}{\psi + 0.35}\right]^2 \tag{15}$$

According to Wark *et al.* (18), In order to account for the effect of Reynolds number, *Re* in the relationship between impaction number and impaction efficiency, an approximation has been developed referred to as *Langmuir approximation.* In the approximation, an estimate of the efficiency is made by first determining the theoretical efficiencies based on viscous flow (Re < 1) and potential flow (Re > 2000) described by (16);

$$\eta_I = \frac{\eta_{vis} + \eta_{pot}\left(\frac{\text{Re}}{60}\right)}{1 + \frac{\text{Re}}{60}} \tag{16}$$

Where, η_{vis} and η_{pot} are the viscous and potential flow efficiencies described by the theoretical curve of Langmuir's approximation shown in Figure-3. The impaction efficiencies for the 1μm, 5μm and 10μm particle sizes were calculated using (16) by first calculating the Reynolds number for the different droplet sizes and then predicting the potential and viscous efficiencies using the theoretical curve in Figure-3.

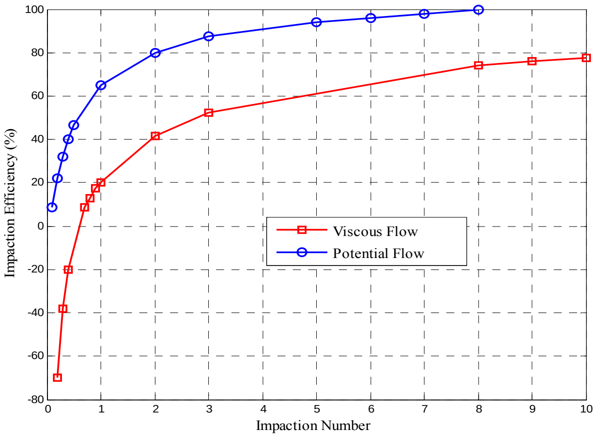

Figure-3. Theoretical curve for langmuir's approximation.

The calculated values for the impaction efficiencies were then presented in Table-7.

2.2.3. Calculations of liquid/gas ratio and gas velocity

Liquid to gas ratio plays a significant role in wet scrubber performance. Considering the recommended liquid to gas ratio which will give an optimum performance of a spray tower scrubber (0.7 - 2.7 l/m^3, USEPA, [17]), In this work, liquid to gas ratios of 0.7, 1.7, and 2.7 l/m^3 were considered. Using the exhaust gas flow rate in Table-1 and the scrubber diameter the gas velocity was calculated to be 0.58m/s using (17).

$$Q_G = A_C\, U_g\,, \tag{17}$$

where Q_G is the exhaust gas flow rate, A_c is the spray tower cross sectional area and U_g is the gas velocity.

3. RESULTS AND DISCUSSIONS

It can be seen that results for 1μm dust particle presented in Table-2 indicated a negative efficiency due to reversed viscous flow within the scrubber system. The maximum efficiency of -3.863% was obtained when the liquid to gas ratio is 0.7l/m^3 and the droplet size is 2000μm while a minimum efficiency of -639726% was obtained at 2.7l/m^3 and 500μm respectively. This shows that, Langmuir's approximation due to viscous flow cannot be applied for dust particle sizes ≤ 1μm. Due to this, only particle sizes of 5μm and 10μm are fully discussed.

Table-7. Calculated values of the impaction efficiencies for different particle sizes.

Re	d_P =1μm ψ_1			d_P = 5μm ψ_2			d_P =10μm ψ_3		
	η_{visc}	η_{pot}	η_I	η_{visc}	η_{pot}	η_I	η_{visc}	η_{pot}	η_I
65.34	-94.74	4.16	-43.19	19.81	64.53	43.12	59.09	91.15	75.80
255.67	-94.74	4.16	-14.64	19.15	64.04	55.51	58.54	90.88	84.73
515.77	-96.45	3.10	-7.28	15.39	61.33	56.54	55.63	89.35	85.83
824.73	-96.45	3.10	-3.65	11.60	58.75	55.55	52.77	87.66	85.29

Considering the maximum removal efficiency of the 5µm dust particle in Table-3, the efficiencies were obtained to be 99.984% at 500µm droplet size and liquid to gas ratio of 2.7 l/m^3 and this is followed by 99.595% and 89.657% at the same droplet size but liquid to gas ratio of 1.7 l/m^3 and 0.7 l/m^3, respectively. On the other hand, the minimum value of the removal efficiency was obtained to be 43.808%, 75.336% and 89.175% when the droplet size is 2000µm at different liquid to gas ratios of 0.7 l/m^3, 1.7 l/m^3 and 2.7 l/m^3. The same trend follows the collection efficiency of 10µm dust particle shown in Table-4, in which the maximum efficiencies was obtained to be 100.000%, 99.994% and 98.147% at constant 500µm droplet size and different liquid togas ratios of 2.7 l/m^3, 1.7 l/m^3 and 1.7 l/m^3 while the minimum value was obtained to be 58.728%, 88.343% and 96.708% at 2000µm, respectively.

As indicated in the graph, the collection efficiency for the removal of both 5µm and 10µm particle sizes decreases with an increase in the droplet size and a decrease in the liquid to gas ratio.

Figure-4 described the summary of the result, graphically showing an exponential relation between the collection efficiency of the scrubber system, the aerodynamic size of the dust particle and liquid droplets size and the ratio of the scrubbing liquid to the gas stream.

But, for an increase in the liquid to gas ratio and a decrease in the droplet size the efficiency increases. From this analysis, it can be deduced that the proposed scrubber system can be used in controlling particle sizes of 5µm and 10µm and it will perform optimally when the droplet size is 500µm and liquid to gas ratio is 2.7 l/m^3.

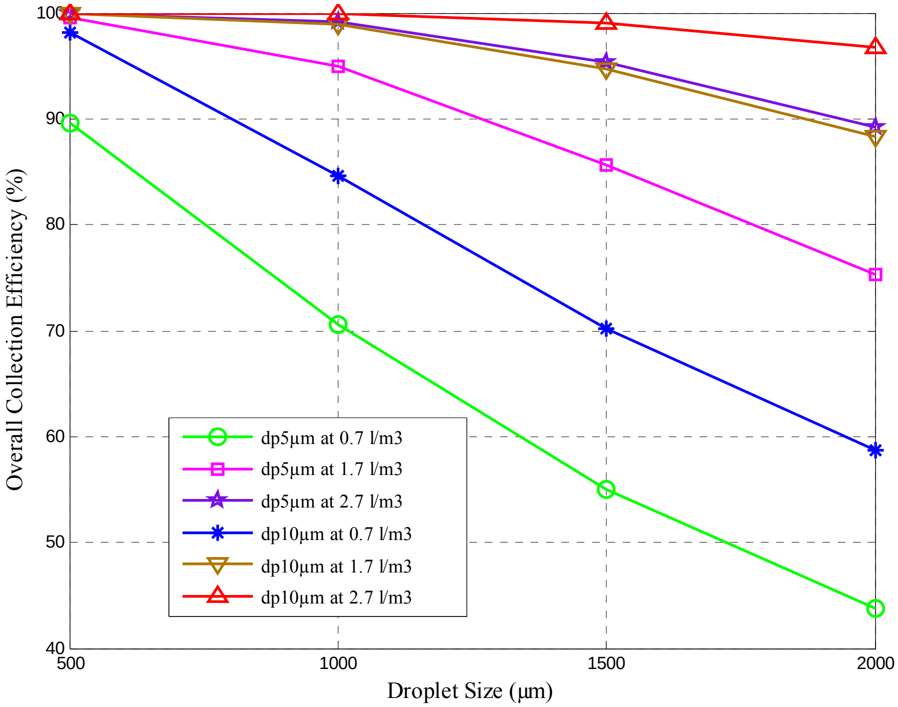

Figure-4. Comparison of overall collection efficiencies for particle sizes of 5µm and 10µm.

4. PERFORMANCE VALIDATION

From the World Health Organization's, WHO [26] annual and 24 hour mean air quality standard for PM$_{10}$, the dust particle concentration must not exceed an annual mean of 20µg/m^3 and a 24-hour mean of 50µg/m^3. Considering this, a model which relates the particulate collection efficiency and the concentration of the dust particle entering the scrubber (dust laden) and the WHO [26] air quality standard concentration was used. This is described by (18):

$$\zeta = \frac{\varphi_{inlet} - \varphi_{WHO}}{\varphi_{inlet}} \tag{18}$$

where ζ is the particulate collection efficiency, φ_{inlet} is the concentration of the dust particle entering the scrubber and φ_{WHO} is the WHO [26] emission standard. From Table-1, the concentration of the exhaust dust laden entering the proposed scrubber is 22, 859µg/m^3 using (18), the required particulate collection efficiency standard for the annual mean emission was obtained to be 99.9125% while that for the 24-hour emission is 99.7813%. These values described the collection efficiency needed by any air pollution control device in order to control the PM$_{10}$ concentration to the WHO [26] standard. Therefore for 24-hour mean emission, $\zeta \geq 99.7813\%$ and for annual mean emission, $\zeta \geq 99.9125\%$.

From the deduction above, it can be said that the performance of the proposed scrubber system is valid by considering the overall collection efficiencies of 99.9884% and 99.595% for the removal of 5μm dust particulate and 100.000%, 99.994% and 99.926% for the control of 10μm dust particulate which has conformed to the WHO standard.

5. CONCLUSIONS

In this study, an analytical method for design and prediction of spray tower scrubber performance based on cement dust particle removal efficiency has been described. The approach focused on the design of a scrubber system for the collection of dust particle sizes of 1μm, 5μm and 10μm (PM_{10}) that are emitted from cement production processes and predicting the performance of the system using Calvert *et al*. model for overall collection efficiency of counter current spray tower by considering droplet sizes of 500μm, 1000μm, 1500μm and 2000μm. The range of liquid to gas ratio of 0.7-2.7l/m^3 recommended by the US Environmental Protection Agency (EPA) were used to investigate the appropriate ratio that will give the optimum result for the performance of the system. The result obtained was validated using the World Health Organisation's air quality standards for particulate matter (PM_{10}).

Due to reversed flow in the Langmuir's approximation, negative collection efficiencies for the 1μm dust particle have been determined. This indicates that Langmuir's approximation cannot be used in the removal of dust particles that are ≤ 1μm. But for the 5μm and 10μm dust particles, the maximum collection efficiencies were determined to be 99.988% and 100.000% at 500μm droplet size and 2.7 l/m^3 while the minimum was obtained to be 43.808% and 58.728% at 2000μm droplet size and 0.7 l/m^3. This indicates that, the optimum performance of a scrubber system can be achieved when the droplet size is 500μm and the liquid to gas ratio is 2.7 l/m^3.

Factors such as the dust particle properties, generation of the dust particles in the scrubber system, lognormal distribution analysis of the dust particles and liquid droplets and spray nozzle and atomization analysis were not considered. The conclusions drawn from the study is that, the proposed system can be used in controlling particle sizes of 5μm and 10μm that are emitted from industrial productions. It is expected that the information provided in this paper will be useful for engineers and researchers for many air pollution control applications especially in the areas of particulate matter (PM_{10}) emissions.

REFERENCES

[1] Kabir G. and Madugu A. I. 2010. Assessment of Environmental Impact on Air Quality by Cement Industry and Mitigating Measures: A Case Study. Environment Monitoring Assessment, DOI 10.1007/s10661-008-0660-4, Springer Science + Business Media B.V. 160: 91-99.

[2] Huntzinger D. N. and Eatmon T. D. 2009. A Life-Cycle Assessment of Portland cement Manufacturing: Comparing the Traditional Process with Alternative Technologies. Journal of Cleaner Production. 17: 668-675.

[3] Ngala G. M. Sulaiman A. I. and Sani M. U. 2008. Air Pollution Control in Cement Factory Using Horizontal Type Wet Scrubber. Continental Journal of Applied Sciences. 3(1).

[4] Frank R. S. and Nancy W. E. 2005. Environmental Engineers Mathematics Handbook. CRC Press, Florida, USA. pp. 208-249.

[5] Makkinejad N. 2001. Temperature Profile in Countercurrent/concurrent Spray Towers. International Journal of Heat and Mass Transfer. 44: 429-442.

[6] Kim H. T., Jung C. H., Oh S. N. and Lee K. W. 2011. Particle Removal Efficiency of Gravitational Wet Scrubber Considering Diffusion, Interception and Impaction. Journal of Environmental Engineering Science. 188(2).

[7] Rahimi A, Taheri M. and Fathikaljahi J. 2002. Mathematical Modeling of Heat and Mass Transfer in Hot Gas Spray Systems. Journal of Chemical Engineering Communications. 189: 959-973.

[8] Bingtao Z. 2005. Modeling of Particle Separation in Bends of Rectangular Cross section. American Journal of Applied Sciences. 2(1): 394-396.

[9] Garba M. N. 2005. Gas Particle Separation Using Wet Scrubber Method. M. Eng Thesis, Department of Mechanical Engineering, Bayero University Kano, Nigeria.

[10] Bozorgi Y., Keshvarz P., Taheri M. and Fathikaljahi J. 2006. Simulation of a Spray Scrubber Performance with Eulerian/Lagrangian Approch in the Aerosol Removing Process. Journal of Hazardous Material B137, 509-517.

[11] Yetilmezsoy K. and Saral A. 2007. Stochastic Modeling Approaches on Neural-Network and Linear Non-linear Regression Techniques for the Determination of Single droplet Collection efficiency Of Countercurrent Spray Towers. Journal of Environmental Modeling and Assessment. 12(1): 13-26.

[12] Passalacqua A. and Fox R. O. 2011. Advanced Continuum Modeling of Gas-Particle Flows in the

hydrodynamic Limit. Journal of Applied Mathematical Modeling. 35: 1616-1627.

[13] Ashaka Cement Company. 2011. Ashaka Company, Feshingo-Jalingo, Funakaye LGA, Gombe State, Nigeria.

[14] Daniel M. and Paula H. 2002. Wet Scrubbers for Particulate Matter. US Environmental Protection Agency, (EPA) Section 6-Particulate Matter Controls, EPA/452/B-02-001,2-20. http://www.epa.gov/ttncatc1/dir1/cs6ch2.pdf.

[15] Cheremisinoff P. N. and Young R. A. 1976. Pollution Engineering Practice Handbook. Ann Arbor Science Inc. Michigan, USA. pp. 125-184.

[16] US Environmental Protection Agency, EPA and National Association of Clean Air Agencies, NACAA. 2012. Control of Particulate Matter Emissions. APTI 413 Module 8 Student Manual. pp. 39-40. www.epa.gov/apti/Materials/APTI413student/413StudentManual/SM_ch8.pdf.

[17] US Environmental Protection Agency. 2011. Design Evaluation of Particulate Wet Scrubber System. SI 412C Module 10, 10-3.

[18] Wark K., Warner C. F. and Wesley A. 1998. Air Pollution, its Origin and Control. Longman Publishers. pp. 10-12.

[19] Abdel-Majid I. M., Mohammed A. H. and Donald R. R. 1997. Modeling Methods for Environmental Engineers. CRC Press. pp. 392-394.

[20] Gunn R and Kinzer G. D. 1949. Terminal Velocity of fall for Water Droplets in Stagnant Air. US Weather Bureau, Washington DC, USA.

[21] Ying X. 2008. Modeling and Direct numerical Simulation (DNS) of Particle-laden Turbulent Flows. PhD Dissertation, Department of Mechanical Engineering, Iowa University, USA.

[22] Joao A. R. 2007. Effect of Silica Fume and SBR Latex on the Paste-aggregate Interfacial Transition Zone. Journal of Material Research. 10(1): 83-86.

[23] Ghosh S. N. 2002. Advances in Cement Technology: Chemistry, Manufacture and Testing. 2nd Edition, Tech Books International, New Delhi, India. p. 741.

[24] Yunus A. C. and John M. C. 2006. Fluid Mechanics: Fundamentals and Applications. Mc Graw Hill Publishers.

[25] Licht W. 1988. Air Pollution Engineering-Basic Calculations for Particulate Collection, 2nd Edition, Marcel Dekker, New York, USA.

[26] World Health Organization-WHO. 2006. Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen dioxide and Sulfur dioxide. Global Update 2005.