OPTIMIZING VERTICAL GAS FLARE STACK'S SIZING PARAMETERS FOR FLARE EFFICIENCY IN NIGER DELTA

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ABSTRACT

One of the performance indicators of a flare system is its ability to consume gases efficiently through combustion so as to produce a more desirable emission. However, this process is significantly affected by the flare operating conditions and sizing (design) parameters. Realistically, this combustion process does not achieve the Ideal efficiency (of 100%), consequently resulting to environmental degradation; hazard to human, plant and animal lives. This study correlates the effect of the flare sizing parameters (diameter and height) of flare stacks in the Niger Delta to their respective efficiencies with a view of finding the optimum design specification that will ensure an efficient operation of flare stacks in the Niger Delta. Seven (7) vertical flare stacks' sizing parameters and their efficiencies, obtained from three (3) different oil and gas companies in the Niger Delta were analyzed by multiple regression using the MS-EXCEL 2016 Suite. From the results obtained, a mathematical model was developed and it showed that the flare's combustion efficiency increased by a factor of 2.44% for every 0.1 metre increase in diameter while holding the other variables constant, while it decreased significantly by 0.64% for every 1 metre increase in the height. The prevailing wind velocity at the stack location was integrated into the model; it was observed that the efficiency decreased as the wind velocity increased under a known period of time. The model showed that flare stacks with diameter of 0.822 metre, height of 18 metre under a wind velocity of less than 15 metre per second for a time interval of 60 seconds performed at 99% efficiency (API standard). However, the mathematical model developed in this study is only valid for predicting combustion efficiency of flare stacks with diameter less than 1 metre and under a wind velocity of less than 15 metres per second.

Keywords: Gas Flare Stack, Sizing Parameters, Flare Efficiency, Niger Delta, Flare stack height, Prevailing wind velocity, Flare stack diameter

INTRODUCTION

The increasing and constant quest of man for energy sources (such as oil and gas) cannot be overstated due to the global high demand for energy consumption. However, during the extraction phase of the oil and gas in an offshore or onshore operation, natural gas associated with the oil and/or free gases are liberated to the surface. Some of the liberated gases are usually lost through flaring process. This process has become a crux requiring so much concern because of its impact on the environment and the economy (where it is carried out). Globally and locally, environmental protection campaign has risen to this challenge by enacting stringent regulatory policies. Some of these policies include; the Kyoto protocol, the associated gas reinjection act of Nigeria 1979 etc. In addition, plethora of utilization options have been and still advocated for as a way of reducing the frequency of gas flaring, yet gas flaring still persists enormously in the oil and gas production facilities in the Niger Delta region of Nigeria. The reasons ranging from operations' safety in pressure relieve valves, a combination of the complex technology and associated cost in gas transportation and

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utilization from production facility. For the area under study, targets have been set by Major oil and gas companies operating in the region to cut down on gas flaring, campaign for flare gas capture, development and utilization is being encouraged by the Nigerian Government through their gas master plan. However, these strategic plans in mitigating gas flaring have not been racy. Research has shown the health of the receiving populace and their ecosystem/environment to be on the decline due to this wasteful process (Adeyemo, 2002; Uyigue and Ogbeibu, 2007; Iyorakpo and Odibikuma, 2015). Gas flaring which is the controlled 'burning' of produced gases in open flames is completed through an emergency release system called the gas flare stack. This stack is usually placed in a remote site of the production facility.

Akeredolu and Sonibare (2004) noted that there are three important indicators by which the performance of most flare systems is evaluated and they are; Flare Combustion Efficiency, Thermal Radiation and Noise Level. The combustion efficiency which is the primary indicator is a measure of how effective the burning process fully oxidizes the fuel (Akeredolu and Sonibare, 2004). Suffice to say that every stack design is usually geared towards ensuring a smokeless operation in a chemistry that involves the natural gas (hydrocarbon) and oxygen so as to give carbon dioxide (a potent Greenhouse Gas) and water as shown in Equation 1.

$$\mathrm{CxHy} + \left(x + \frac{y}{4}\right) O_2 \rightarrow xCO_2 + \left(\frac{y}{2}\right) H_2O \qquad 1$$

Equation 2 below is a mathematical representation of flare Combustion Efficiency (CE) as stated by Akeredolu and Sonibare (2004).

$$\mathrm{CE}\ (\%) = \frac{CO_2}{CO_2 + CO + THC} \qquad 2$$

With the high prevalence of gas flaring in the Niger Delta and matching the enormous devastations it has brought to the target environment through these flare performance indicators, obviously an optimization of the process would prove to be helpful. This optimization through improved technology of the stack design becomes a necessity as an environmental management approach in mitigating the adverse environmental impacts of gas flaring. According to John et al (2013) optimization of the flare operation can be achieved by carefully addressing some of the parameters that affect the combustion efficiency of the flare system. While the chase and wait for the actualization of gas flare reduction continues, this technology lays emphasis on improving the combustion efficiency (through proper sizing of the flare stack) so as to have a safe flare- devoid of Carbon monoxide and other particulates. This research article proposes a mathematical model that predicts the varying effects of vertical flare stack sizing parameters on the flare efficiency, with a view of ensuring an efficient gas flaring process in the Niger Delta. There is a combination of the important factors which the flare vendor influences and those undeterminable by the vendor but however affect the flare system design and performance. Ling (2007) noted the following; feed gas composition, gas condition, utilities available (gas, air, steam) for assisted flares, environmental and safety conditions, Site and climate condition and Cost. This gives the operator knowledge of the presence of entrained impurities like H2S, which needs special metallurgy design. Ling (2007) noted that a high ratio of Hydrogen to Carbon yields a smokeless flame whereas a low ratio considerably generates a smoky but luminous flame.

METHODOLOGY

Figure 1 shows the model design flow chat.

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Figure 1. Model design flow chat

Sizing a Flare Stack

With a lot of parameters playing significant roles in the design of a flare stack, the flare tip type (diameter) and the stack elevation (height) form the key parameters of this system (API 2007).

Flare Tip

Which could also be seen as the flare header diameter is usually sized relative to the velocity of the gas stream and that of the assisted-fluid stream (for assisted flares). An accurate determination of the flare diameter is important in ensuring a safe and hazard free operation. Equation 3 below is a simple approach to sizing the flare header (API 2007).

$$D2 = 3.23 \times 10\text{-}5 \left[\frac{Q_m}{p_2 Ma_2}\right]\left[\frac{ZT}{M}\right]^{0.5} \qquad 3$$

Flare Height

The height of the flare stack is generally sized on Radiant-heat Intensity basis. Optimum flare stack height sizing is usually required seeing that this distance relative to ground level gives what the expected thermal radiation would be (assuming humans and property at the ground

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level). API (2007) citing Hajeck and Ludwig, related the radiant-heat intensity and flare stack elevation using equation 4 below;

$$H = \sqrt{\frac{nFQ}{4\pi K}} \qquad 4$$

Data Collection

Secondary data (shown in Table 1) was utilized for this research work; the relevant data (stack diameter, stack height and their corresponding combustion efficiencies) were obtained from 7 flare stacks within the Niger Delta province. To establish a valid mathematical model that relates the varying effects of these stacks's sizing parameters on the flare performance (efficiency), data sample points were taken while maintaining appreciable distances among the different sample locations. The research design, data collection and management took into consideration a few established correlations on pressure-relieving systems' sizing and statistical analysis (API. 2007; Nwaogazie, 2011; John et al, 2013). All of these aimed at ensuring that the process leading to the derivation of the predictive model is systematic and methodological.

Table 1. Sizing Parameters and Combustion Efficiencies

FLARE STACKS	DIAMETER (Meters)	HEIGHT (Meters)	EFFICIENCY (%)
Stack 1	0.7680	37.8125	83.0000
Stack 2	0.4697	22.6406	88.5000
Stack 3	0.7692	18.8000	98.8600
Stack 4	0.6154	17.7500	92.0000
Stack 5	0.6205	22.5625	88.6000
Stack 6	0.9231	30.4500	96.6900
Stack 7	0.3205	24.6250	85.0000

It is imperative to state that the acquired data were obtained with the following conditions which cannot be dispensed in the final mathematical model;

Flare stacks' combustion efficiencies only to handle a Wind Velocity of 1m/s to 15m/s.

The efficiencies obtained were average combustion efficiencies within a specified time period.

It was observed from the data that they were linearly correlated, thus the mathematical fitting equation (Equation 5) was assumed for the data.

$$Y = a_0 + a_1 X_1 + a_2 X_2 \qquad 5$$

Y = Efficiency of the Flare Stack (in %).

X_1= Stack tip diameter, M.

X_2 =Height of Flare Stack, M.

a_0, a_1, a_2= Constants.

Multiple regression analysis was carried out on the acquired data with the use of MS-EXCEL 2016 Package under a confidence level of 95%. The following hypotheses were stated for the analysis;

Null Hypothesis, H_O: $a_1 = a_2 = 0$, There is no relationship between that sizing parameter to flare performance (efficiency) and if any, it may have occurred by chance.

Alternative Hypothesis, H_1: $a_1 = a_2 \neq 0$, There exist a relationship between that sizing parameter to flare performance.

RESULTS AND DISCUSSION

A summary of the obtained result from the multiple regression analysis is shown in Figure 2.

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.910763446							
R Square	0.829490055							
Adjusted R Square	0.744235083							
Standard Error	2.952240128							
Observations	7							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	2	169.5995986	84.79979931	9.729521147	0.029073641			
Residual	4	34.8628871	8.715721774					
Total	6	204.4624857						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	90.746201	5.039444349	18.00718387	5.59103E-05	76.7544604	104.7379416	76.7544604	104.7379416
DIA (m)	24.3648791	6.408101006	3.802199604	0.01906755	6.573138433	42.15661977	6.573138433	42.15661977
HGT (m)	-0.640652864	0.184312604	-3.475903714	0.025446568	-1.152386691	-0.128919038	-1.152386691	-0.128919038

Figure 2. Summary output of the multiple regression analysis

On extraction of the respective slope values for Diameter, Height and the intercept yields the predictive model below;

$$\text{EFF} = 90.7462 + 24.3648\text{D} - 0.6406\text{H} \qquad 6$$

The adequacy of the model has been judged by its resultant Coefficient of Correlation, R2, which is a measure of the goodness of fit of the mathematical model to the given data. An R2 value (as marked in Red from Figure 2) of 0.829490055 was obtained, which means that the model represents a minimum of 82.94% of the data which is desirable. From the Analysis of Variance (ANOVA), the model recorded a Significance Level of 2.9073% (as marked in Green in figure 2), which means that the model can be accepted with a Confidence Level of 97.09%. The resulting coefficients a_0, a_1 and a_2 which are respectively 90.746201, 24.3648791 and -0.640652864 (as marked in Blue in Figure 2) are not equal to Zero. Thus when judged against the set hypotheses, the null hypothesis has been rejected and the alternative hypothesis accepted. In a similar way, the diameter and height showed a marked significance in the multiple regression analysis as seen in their respective P-Values (as marked in Orange from Figure 2).

Factor of Safety

As a necessity to validate the mathematical model, a factor of safety which puts into consideration the indispensable conditions under which the regressed data were acquired had to be integrated into the generalized model, thus the final model becomes;

$$\mathrm{EFF} = 90.7462 + 24.3648\mathrm{D} - 0.6406\mathrm{H} - \mathrm{M}* \qquad 7$$

$$\text{Where, } \mathrm{M}^* = [\mathrm{Log}\,(\nu_{\sim} * \Delta\mathrm{T}] \qquad 8$$

Given that; $1\mathrm{m/s} \leq \nu_{\sim} \leq 15\mathrm{m/s}$ within an interval of 1 hour.

The factor of safety corroborates the fact that combustion efficiency is reduced by high wind velocity (high above the flare Jet).

Residuals

Figure 3 shows the residuals of the output variable to the model with the lower and upper limits of the residuals as -2.809878233 and 2.960458816 respectively.

RESIDUAL OUTPUT		
Observation	*Predicted EFFICIENCY (%)*	*Residuals*
1	85.23374172	-2.233741722
2	82.77906797	2.22093203
3	87.68561948	0.814380524
4	91.40987823	-2.809878233
5	94.36875926	-2.368759258
6	97.44339216	1.416607843
7	93.72954118	2.960458816

Figure 3. Mathematical model residual outputs

Figure 4 displays a trend view of the different stack sizing parameters as it depicts their varying effects (correlation) on the combustion efficiency. The trend analysis showed that the efficiency increased as the stack diameter increased. However, an increase in height caused a reduction in the combustion efficiency. This is in consonance to the fact that the pressure of a fluid decreases as the upward height increases, making it difficult for the flare gas to acquire the required pressure necessary to ensure an efficient combustion process. Correspondingly, the amount of oxygen (a major reactant component in combustion process) decreased with increase in altitude. Thus, an increase in stack height brings about a corresponding decrease in the amount of oxygen made available for the combustion process, which eventually affects flare performance.

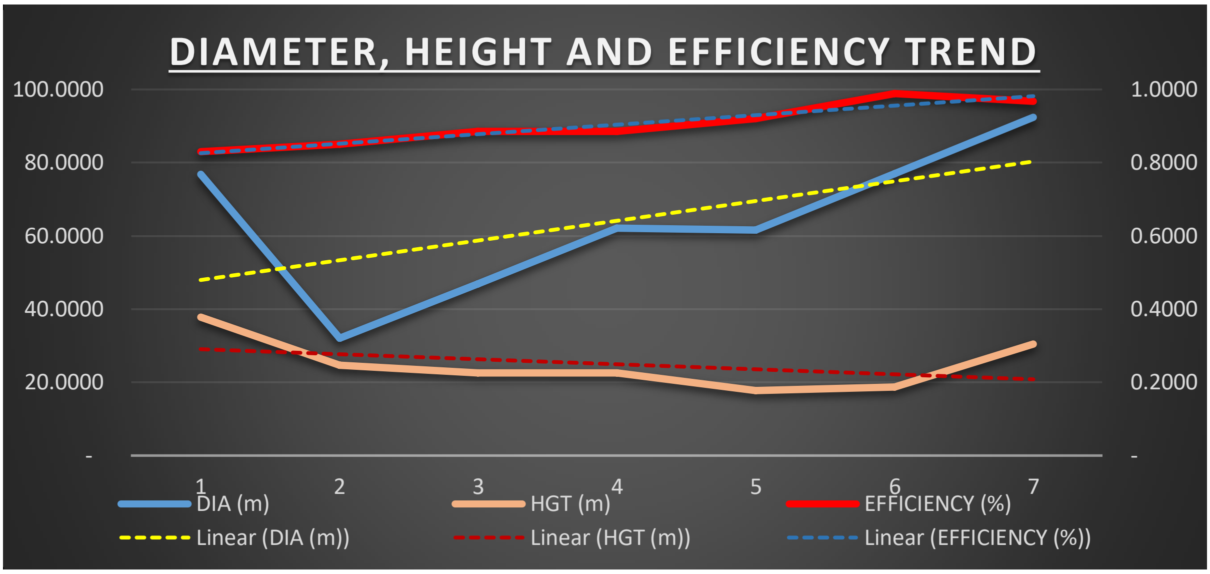

Figure 4. Diameter, height and efficiency trend view

CONCLUSION

1. The cessation of gas flaring in the oil and gas operation facilities in Nigeria has become an onerous task. While the campaign to stop flaring continues, this research work gives a first-line, an easy-to-do, a technologically inexpensive and dependable management approach in ensuring that gas flaring in the Niger Delta has less environmental impact, with a view that waste management begins with waste minimization.
2. This study showed that the sizing parameters are greatly significant in predicting the flare efficiency.
3. The model developed is valid only for vertical flares stacks of 0.256 to 0.9216 meters in diameter that are operating in wind speeds of less than 15 minutes per second, thus the operating and sizing conditions of the stack should be considered and verified to have met API standards before applying the stated mathematical model.
4. Flare gas utilization remains the best option in mitigating gas flaring, thus it should be the priority of every oil and gas company still involved with gas flaring.

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Annexture - I

Nomenclature

CO_2	Carbon dioxide.
CO	Carbon monoxide.
THC	Total Hydrocarbon.
Q_m	Gas mass flow rate, in Kg/hr (or lb/hr)
Z	Gas compressibility factor
T	Absolute Temperature,
K.M	Gas relative molecular mass.
D	Stack inside diameter,
M. P_2	Stack outlet Absolute Pressure,
Kpa.	
Ma_2	Mach number at Stack outlet.
D	Minimum distance from the epicentre of the flame to the object being considered,
M.n	Fraction of the radiated heat transmitted through the atmosphere.
F	Fraction of heat radiated.
Q	The heat released, kW (Btu/h).
K	The radiant heat intensity, in kW/m2 (Btu/h·ft2).
M*	Meteorological Factor.
$V_\sim$	prevailing wind velocity at the flare site in M/S.
ΔT	Evaluation time interval, Seconds.