



Exergy analysis of waste emissions from gas flaring

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Abstract

Gas flaring produces a stream of waste gases at high temperature and pressure which contains carbon monoxide, Hydrogen Sulphide etc. The resultant effect of which is detrimental to our planet and, consequently, to the life of both the living and the non-living things. It's well known that gas flaring contributes in no small measure to the global warming. Exergy analysis is applied in this work to analyze waste emissions from gas flaring so as to have a model through which impact of gas flaring can be measured. The study considers both the thermo-mechanical exergy and the chemical exergy of these gases. Relevant data on gas flaring activities in the Niger-Delta region of Nigeria between the periods of fifteen (15) years was obtained from the Nigerian National Petroleum Corporation (NNPC). A computer program (Exergy Calculator) was developed based on the equations generated in the Model. Exergy associated with gas flaring activities in Nigeria between the periods of 1998 through 2012 was calculated. The results show that 1 mscf (in thousand cubic feet) of flared gases generate 0.000041 MWh of energy leading to a value of 440158.607 MWh of energy for the period under review. The analysis provides important conclusions and recommendations for improving oil platforms operations in order to safeguard the environment, health of the populace, and maximize recovered exergy from gas flaring.

Keywords

Exergy; Gas Flaring; Exergy Calculator; Flare Stack; Associated Gases; Environmental Degradation; Niger-Delta

Introduction

The phenomenon of gas flaring and associated environmental degradation is well known. This has been generating lots of debates over time. One will wonder, why will oil companies allow all of these gases that should be of economic values to be wasted as it is presently the practice? Why has it been difficult for the Oil Companies to tap into the economic benefits offered by proper usage of the flared gases? Better still, the question could be posed: "are there enough benefits (environmental or commercial) in these gases to justify the huge capital investment that would have to be made in them?" Therefore, there is need to carry out exergy analysis on the waste emissions vis-à-vis their economic values and effects on the environment.

Gas flaring is the burning of natural gas that is associated with crude oil when it is pumped up from the ground. In petroleum-producing areas where insufficient investment is made in infrastructure to utilize natural gas, flaring is employed to dispose of these associated gases. This produces emissions which degrade the environment and are harmful to both living things and non living things, reducing it as much as possible should be the concern to all [1]. Various gases emitted includes Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulphurhexafluoride (SF_6), sulphur dioxide (SO_2), hydrogen sulphide (H_2S), unburned fuel, particulate soot and other by-products of combustion [2-6], effort should be made to reduce these emissions [7] since there is a threshold which can be tolerated by habitats living in the environment [8].

Exergy analysis is applied in this work to analyze waste emissions from gas flaring in order to have a model through which its impact can be measured. Exergy analysis has been used over the years for different applications [9-14].

Exergy analysis is based upon the second law of thermodynamics, which stipulates that all macroscopic processes are irreversible. Every such irreversible process entails a non-recoverable loss of exergy, expressed as the product of the ambient temperature and the entropy generated. Some of the components of entropy generation can be negative, but the sum is always positive [15].

A complete set of updated values of chemical exergies of elements at standard conditions (298.15K and 1 atm) has been tabulated to easy regional calculation in exergy analysis [16]. Their values will be adopted for this work.

Material and method

Exergy, basically, is of two types: (1) Thermo-mechanical Exergy and (2) Chemical Exergy.

Thermo-mechanical exergy is the exergy associated with the conversion of thermal energy to mechanical energy and disregards any mixing and chemical reactions. Depending on the type of system involved, the following types of thermo-mechanical exergy exist:

Potential energy which is expressed as:

$$PE_{exergy} = mgz \quad (1)$$

where PE_{exergy} : potential exergy (kJ), m : mass of gas (kg), z : elevation above a datum (m).

Kinetic energy which is expressed as:

$$KE_{exergy} = \frac{1}{2} mc^2 \quad (2)$$

where KE_{exergy} : kinetic exergy (kJ), c : velocity of the gas (m/s).

Reversible and Irreversibility: Reversible work is determined from the exergy balance relations by setting the exergy destroyed equal to zero. The work, W , in that case becomes the reversible work. The irreversibility associated with gas flaring in Nigeria is 100% as all of the gases produced are flared off. Therefore,

$$W_{useful} = W_{rev} - W_{surrounding} = W - P_{surrounding} (v_2 - v_1) \quad (3)$$

where W_{useful} : useful work (kJ), W_{rev} : reversible work (kJ), $W_{surrounding}$: work done on the surrounding (kJ), $P_{surrounding}$: surrounding pressure (kPa) and v_2-v_1 : change in volume (m^3).

$$I_{irreversible} = W_{rev,out} - W_{useful,out} \quad \text{or} \quad I = W_{useful,in} - W_{rev,in} \quad (4)$$

where $I_{irreversible}$ ($= I$): Irreversibility (kJ), $W_{rev,out}$: reversible work out (kJ), $W_{useful,out}$: useful work out (kJ), $W_{useful,in}$: useful work in (Kj), $W_{rev,in}$: Reversible work in (kJ).

The exergy of a system that is in equilibrium with its environment is zero. For the purpose of this study the state of the environment will be regarded as 'dead state' as practically no useful work can be derived from it. Flared gases are often ejected into the atmosphere in a state totally different from that of the environment. Hence, appreciable amount of exergy is embedded in these gases while it is being brought to equilibrium with environment. This difference in both the states of gases and environment necessitates the change (exergy) in the system.

Since Flared gases are constantly in motion and often involve transfer of masses

across the system boundary which makes it to be likened to a control volume, the flow (or stream) conservation exergy equation is used.

The exergy of fixed mass (Non-flow) system is given by

$$Exergy_{nonflow} = (U - U_{surr}) + P_{surr} (V - V_{surr}) - T_{surr} (S - S_{surr}) + \frac{1}{2} mc^2 + mgz \quad (5)$$

where $Exergy_{nonflow}$: Non-flow exergy (kJ), U : System Internal Energy (kJ), U_{surr} : surrounding internal energy (kJ), V : system volume (m^3), V_{surr} : surrounding volume (m^3), T_{surr} : surrounding temperature (K), S_{surr} : entropy of the surrounding (kJ/K), S : entropy of the system (kJ/K).

But for flow system, there is an additional form of energy, called the flow energy, which is the energy, needed to maintain flow in a pipe or duct, and was expressed as:

$$W_{flow} = Pv \quad (6)$$

where W_{flow} : flow work (kJ), P : system pressure (kPa), v : specific volume of the fluid (m^3/kg)

Flow work is essentially the boundary work done by the fluid on the fluid downstream, and thus the exergy associated with flow work is equivalent to the exergy associated with the boundary work. This is simply the difference between the boundary work and the work done on the environment. Noting that flow work is $P \cdot v$ and the work done against the atmosphere is $P_{surr} \cdot v$; the exergy associated with flow energy can be expressed as:

$$Exergy_{flow} = Pv - P_{surr} v = (P - P_{surr})v \quad (7)$$

where $Exergy_{flow}$: flow exergy (kJ).

The Total Thermo-Mechanical Exergy (Ψ) is obtained by addition of equations (5) and (7) i.e. $\Psi = Exergy_{nonflow} + Exergy_{flow}$. Cumulating:

$$\begin{aligned} \psi &= (U - U_{surr}) + P_{surr} (V - V_{surr}) - T_{surr} (S - S_{surr}) + \frac{1}{2} mc^2 + mgz + (P - P_{surr})v \\ &= (u + Pv) - (U_{surr} + P_{surr} V_{surr}) - T_{surr} (s - s_{surr}) + \frac{1}{2} c^2 + gz \end{aligned} \quad (8)$$

Thus,

$$\psi = (h - h_{surr}) - T_{surr} (s - s_{surr}) + \frac{1}{2} c^2 + gz \quad (9)$$

where h : enthalpy of the system (kJ), h_{surr} : enthalpy of the surrounding (kJ).

The chemical exergy of a substance is the maximum work that can be obtained from it by taking it to chemical equilibrium with reference to the environment at constant temperature

and pressure. With this definition, the environment has zero exergy but other air composition would have chemical exergy (E_{ch}) greater than zero. Table 1 show various substances with their molar chemical exergy.

Table 1. Molar exergy, (E_{ch_i}), of pure species relative to a reference atmosphere at $P_0=100$ kPa, $T_0=25$ °C, and 60% RH; $E_{ch_i} = \mu_i(T_0, P_0, 1) - \mu_{i0}(T_0, P_0, X_{i0})$

Substance	Formula (state)	Molar fraction in ref. atm. (X_i)	Molar exergy (E_{ch_i}) [kJ/mol]
Nitrogen	N ₂ (g)	0.7651	0.66
Oxygen	O ₂ (g)	0.2062	3.9
Water	H ₂ O(l)	0.0190	1.3
Argon	Ar(g)	0.0094	12
Carbon dioxide	CO ₂ (g)	0.0003	20
Carbon monoxide	CO(g)	NA	275
Hydrogen	H ₂ (g)	NA	236
Methane	CH ₄ (g)	NA	831
Ethane	C ₂ H ₆ (g)	NA	1500
Ethylene	C ₂ H ₄ (g)	NA	1360
Acetylene	C ₂ H ₂ (g)	NA	1265
Propane	C ₃ H ₈ (g)	NA	2150
n-Butane	C ₄ H ₁₀ (l)	NA	2800
Carbon (graphite)	C(s)	NA	410
Nitrogen monoxide	NO(g)	NA	89
Nitrogen dioxide	NO ₂ (g)	NA	56
Ammonia	NH ₃ (g)	NA	340
Methanol	CH ₃ OH(l)	NA	720
Ethanol	CH ₃ CH ₂ OH(l)	NA	1400

Source: Isidoro Martinez, 'Chemical Exergy', 2005. [17]

The molar exergy of the pure component, at T_0 , P_0 , and if in gaseous state, is:

$$E_{ch_i} = R_u T \cdot \ln(x_{i0}) \quad (10)$$

where E_{ch_i} is the chemical exergy of the constituent gases (kJ), $R_u = 8.314\text{J}/(\text{mol}\cdot\text{K})$, $T^* = 298.15\text{K}$, and x_{i0} its molar fraction in the environment, T_0 , $P_0 =$ surrounding temperature (K) and pressure (Kpa) respectively.

For substances not in the reference atmosphere (but with all of its different atoms represented in the environment), e.g. for CO, a chemical reaction must be set to produce it from the existing species in the environment, for example, $\text{CO}_2 = \text{CO} + (1/2) \text{O}_2$.

For substances not in the reference atmosphere (but with all of its different atoms represented in the environment), e.g. for CO, a chemical reaction must be set to produce it from the existing species in the environment, e.g. $\text{CO}_2 = \text{CO} + (1/2)\text{O}_2$.

Therefore, the general exergy equation of any system is the combination of the thermo-mechanical exergy (flow + Non-flow) and chemical exergy.

Thus:

$$Exergy_{general} = \psi + E_{ch} \quad (11)$$

where $Exergy_{general}$ = General Exergy (Total exergy) (kJ).

$$Exergy_{general} = (h - h_{surr}) - T_{surr} (s - s_{surr}) + \frac{1}{2} c^2 + gz + E_{ch_i} \quad (12)$$

where E_{ch_i} = Chemical exergy of the constituent gases (kJ).

For the case of flare gases, where difference by-products are involved equation 12 becomes:

$$Exergy_{general} = (h - h_{surr}) - T_{surr} (s - s_{surr}) + \frac{1}{2} c^2 + gz + n_i E_{ch_i} \quad (13)$$

where n_i = no of moles of constituent gases (mol)

$$Exergy_{general} = (h_i - h_{surr}) - T_{surr} (s_i - s_{surr}) + \frac{1}{2} c^2 + gz + n_i E_{ch_i} \quad (14)$$

where s_i = entropy of constituent gases (kJ/K), h_i = enthalpy of constituent gases (kJ).

But:

$$(h_i - h_{surr}) = C_{pi} (T - T_{surr})$$

where C_{pi} : specific heat at constant pressure of constituent gases (kJ/K).

Also:

$$(s_i - s_{surr}) \cong \left(C_{pi} \ln \frac{T_2}{T_1} - R_u \ln \frac{P_2}{P_1} \right) \quad (15)$$

where T_1, T_2 : initial and final temperatures (K), P_1, P_2 : initial and final pressures (kPa)

Hence, equation (13) becomes:

$$Exergy_{general} = C_{pi} (T - T_{surr}) - T_{surr} \left(C_{pi} \ln \frac{T_2}{T_1} - R_u \ln \frac{P_2}{P_1} \right) + \frac{1}{2} c^2 + gz + n_i E_{ch_i} \quad (16)$$

$$n_i = \frac{P_2 V_{2,i}}{R_u T_2} \quad (17)$$

where $V_{2,i}$ = final volume of constituent gases (m^3).

The constituents of the flared gas were taken from the work of AbdulKareem [18] as shown in Table 2.

The analysis was conducted as given in Figure 1

Table 2. Percentage by volume of hydrocarbons in flared gas in an oil station in Niger-Delta area

Components	CH ₄	C ₂ H ₆	C ₃ H ₈	C ₄ H ₁₀	C ₅ H ₁₂	Others
% Composition by volume	47	18	20	5	9	1

Source: Abdulkareem [18]

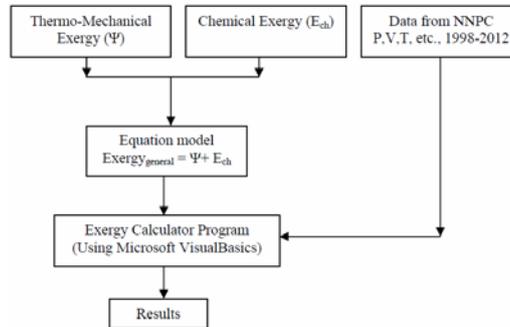


Figure 1. The algorithm of the present work

Results and discussion

Gas flaring has proven to be a major contributor to the generation of Green House Gases (GHG) which consequently has serious negative impacts on the natural environment. In as much as the modern economic development depends largely on the use of technologies driven by power generated through hydrocarbons, oil exploration will continue to play a dominant role in man’s quest for energy. Unfortunately, this process leads to flaring of associated gases (as it is presently the practice) which constitutes serious environmental challenges to our ecosystems. A computer program (Exergy Calculator) was developed (Figure 2) based on the equations generated above using Microsoft Visual Basic 6.0 Software (Working Edition).



Figure 2. Interface of the Exergy Calculator developed

The program was tested and the results are consistent with the equations given. With the software developed (Figure 3), the exergy of flared gases for the period under review (i.e.

1998 - 2012) is as given in Table 3. 440,158.607 Megawatt-hour (MWh) of Exergy was generated through flared gases over the period of fifteen years. This is an enormous energy considering the fact that the average power generation in Nigeria over the period is 2,800 Megawatt-hour (MWh).

Table 3. Results of gas flared Vs. Exergy from 1998-2012

Years	Volume of flared gas (mscf)	Exergy (MWh)
1998	834,542,305	34234.632
1999	792,247,965	32499.634
2000	882,760,070	36212.624
2001	920,905,671	37777.436
2002	744,108,035	30524.834
2003	846,013,629	34705.208
2004	886,070,556	36348.424
2005	812,332,777	33323.552
2006	799,998,368.20	32817.57
2007	789,546,171.84	32388.796
2008	631,188,574.46	25892.646
2009	824,262.75	33.815
2010	581,568,353.85	23857.124
2011	619,032,858.01	25393.998
2012	588,666,724.18	24148.314

Since there is fine attached to the volume of flared gases in Nigeria there has been allegations of underreporting by the Oil Multinationals, hence, data acquired through the use of satellite was adjudged to be more accurate in giving true picture of gas flared (Figure 2).

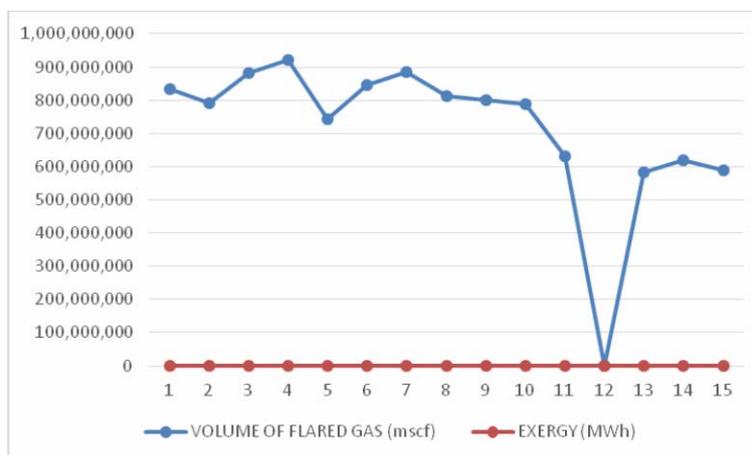


Figure 3. Graph of Gas flared vs. Exergy

With the present practice, an average of 78 % of our natural is being flared on the daily basis not minding the attendant effect of global warming. More so, Nigeria cannot afford to sit back and watch her natural resources to continue wasting in this manner of gas flaring. The should form a synergy in addressing this monumental wastage of resources and

global environmental – health calamity. Gas flaring must time to act is now and all stakeholders in the energy, environmental, and health sectors stop.

Conclusions

In the course of carrying out this study it was discovered that huge amount of exergy always accompany every cubic feet of flared gas in the Niger-Delta region of Nigeria. Also, observation was made that these are useful energies that if properly harnessed should have translated into generation of several megawatt-hours (MWh) of electricity.

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