

NATURAL GAS OPERATIONS IN NIGERIA'S NIGER DELTA: AN ENVIRONMENTAL AND THERMODYNAMIC EXAMINATION

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Abstract

This research focuses on flared oil field gaseous substances, its thermodynamic and hazardous effect in the Nigerian Niger Delta area. It examines the consequences of flue-gases in the area, the region subjection to too many sorts of contamination and deterioration rising from oil and natural gas extraction. These include a decline in agricultural production, negative effect on freshwater, deformities in children, disorders in human complexion, pollution levels in the air, soil acidity, metal roof deteriorated, sulphates, nitrates, and dissolved solids as well as accompanying socio-economic concerns amongst others. Despite the fact that decree 99 prohibits unlawful flaring, almost 75% of the gas generated is being flared. There has not been much empirical study on the effects of gas flaring on the physical, chemical, biological, atmospheric, and social environment according to the report. It concludes that a thorough inquiry and evaluation of the consequences of gas flaring on the Niger Delta's multiple environmental sections is urgently needed, since this is a prerequisite for realizing the ideal of sustainable mineral extraction in the area. Data used was gathered throughout a nine-year period for this report (2010-2018) with production quantities, volumes of flared components, operational temperature, pressure, gas compositions, gas density, and flow rates as factors considered and reported. Analysis of combustion was carried out using the data, MATLAB computer codes and the basic thermodynamic equations to determine the quantity of flared gases. Analyses revealed that during the time period in question, an overall 1.99175×10^{11} gas volume in standard cubic feet was flared, resulting in anthropogenic $582,319,618.1826\text{m}^3$ (≈ 1.046 Mt) CO₂ emissions, $1,077,510,054.32\text{m}^3$ (≈ 2.0 Mt) water vapour emissions, including $14,960,560.91\text{m}^3$ methane emissions and contamination to the area therefore posing serious environmental worries. More analysis revealed that the estimated adiabatic flame temperature for the field under examination was around 1965°C. Exergy investigations found that there was an overall 3.6099×10^{13} kJ (36.099 TJ) of exergy accessible, equating to 1.0189×10^{10} kWh of electrical power for the duration under examination. Finally, carbon capture technology could be improved, but given the huge quantity of carbon (IV) oxide and other gaseous compounds represented in the data, the best choice is to flare out. The entire project and its findings demonstrated suchlike, because of its thermal, environmental, and economic consequences; flue gas is undesired and damaging. Also to minimize gas flaring, every new project ought to include practical specifics for gas collection plus usage plans throughout the engineering design stage up to product commercialization, and as well as construction of many gas plants to convert the gas to electrical power and other commercial use.

Keywords: Carbon (IV) oxide, exergy, combustion, adiabatic flame temperature, gas flaring.

Introduction

Significant progress recorded in the world today has been discovery of hydrocarbons, energy conversion, consumption, particularly electricity throughout human history. This is majorly a function of population growth. Any society's level of living is linked to its energy use (Hart 2018). After half a century of investigation, in 1956, oil was found in Nigeria near Oloibiri, presently part of Bayelsa state. Shell-BP, the concessionaire at the time, made the finding. Nigeria's first oil field began producing 5,100 barrels per day in 1958, marking the beginning of the country's oil production. Exploration and production of oil and gas activities are undeniably important for the economic growth of countries possessing such natural resources. It generates income and sustains economies all around the world, especially when well managed (Nii 2005). However, it is important to note that crude oil production has negative implications.

Hydrocarbon is a mixture of natural gases, water, and other contaminants. Associated natural gas is the gas that is associated with crude oil. In an ideal world, these gases would have been captured and sold to customers or used to generate energy, but pipelines, gas collection facilities, power plants, and other associated infrastructure, on the other hand, are costly investments to make it possible. In fact, oil corporations choose to trade the crude while burning the gas. Since the discovery of crude oil in commercial quantity, gas has been flared continuously. No importance was attached to the discovery because as at the time, it was thought to be a bothersome by-product, with little understanding about its prospect. Flaring was the sole option because it had no processing facilities. Another explanation for the continual gas flare is multinational corporations' complacency.

The country is now amongst the highest gas-flaring country in the world, down from second place ten years ago (Chineme 2017), demonstrating that significant efforts are being made to reduce gas flaring. Access to a dependable and consistent source of power in Nigeria is a serious concern for both urban and rural residents. Electrical demand considerably outstrips availability, according to several studies of Nigeria's electricity supply challenges and possibilities (Oyedepo et al. 2013).

Nigeria produces just 4000 megawatts of power, far insufficient for its people, but squanders a significant source of energy for over 50 years, and thus this fact-finding here is aim at designing to evaluating thermo-mechanical and environmental impacts of emission due to flaring, alternative use to power gas turbines, fuel for steam engines, condense gas by Fisch-er-Tropsch procedure, collect, compress, re-injecting gas into oil wells to improve oil recovery and other possible applications.

The bulk of the research found that the majority of the impacts of gas flares are thermal in nature due to exit temperatures and considerable environmental repercussions. Using computational approaches, reference (Ismial and Fagbenle 2009) created a model for accurately predicting heat flow in any area of operation. (Abdulkadir et al. 2013) used four

communities for examination to investigate the consequences of gas operation based on amount of CO₂ emitted. Their research revealed that the amount of CO₂ created exceeds the essential threshold level (about 30,000 ppm). To calculate the amount of flared gas, (Tsokos and Xu 2009) employed a set of equations in their model study.

(Aniefiok and Udo 2013) found that gas flaring had an influence on soil temperature, its moisture content, PH value and microorganisms, particularly due to thermal impacts. Flaring contaminates water bodies, according to common perception (Abdulkadir et al. 2013; Ubani and Onyejekwe 2013; Aniefiok and Udo 2013) and also negatively affect the ecosystems. The influence of gas flaring on environmental pollutants, health consequences, economical challenges, and host community harm was investigated (Dung et al. 2008). According to their findings, inorganic substances, volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs) pollutants are all produced by incomplete combustion.

According to (Ismail and Umukoro 2012), soot and acid rain accumulation on rooftops are another condition exacerbating hazard. As a consequence, the acidity of precipitation in the Niger Delta seems to be greater than elsewhere. Bibliography at various positions from a flare point in a case study, crop leaf lengths and widths, their heights, and all of the yields of cassava and other crops were measured. Due to thermal pollution inside the flare radius, cassava yields were also greater in places farther away from flare sites.

(Sosimo et al. 2012) used an extended energy accounting technique to quantify environmental externalities linked with chemical pollutants generated by a high flare stack in terms of energy. This research estimated the energy flow flare stack fired into the environment as well as the equal cost in basic resources. Energy analysis was utilized in reference (Ismail and Adewale 2012) to analyse the environmental impact potential of systems and enhance system performance by reducing waste emissions. A system not in thermal balance with its surroundings releases energy, according to this theory. They further said that releasing emissions by our systems is equivalent to releasing energy to the atmosphere, which in addition is not just reducing system's effectiveness plus wastes, rather accelerate global warming. There are similarities between the studies of references, (Sosimo et al. 2012; Ismail and Adewale 2012; Olawale and Kazeem 2016), however (Olawale and Kazeem 2016) undertook considerable work on energy, a study of trash emitted by gas flares in order to develop a means by which the repercussion of flared gases may be quantified. Gas stream was treated as an ideal gas in their analysis, laws and equations governing behavior of ideal gases were utilized.

Rule of thumb and exergy accounting were employed in reference (Nguyen et al. 2013), including Aspen HYSYS plus, Dynamic Network analysis for evaluation and assessment of thermodynamics an oil and gas platform's performance. Power generating and waste heat recovery

systems accounted for 62 percent–65 percent of the total energy destruction on the offshore platform, while oil and gas processing accounted for 35 percent–38 percent.

They confirmed that high-temperature gas rejection from flare and utility systems is a significant contribution to energy waste. The technology of using Carbon capture combined with environmental and thermal studies was not done in most of the literature studied, which is one of the flaws this article identifies. Furthermore, heat fluxes were meticulously computed in this study, revealing the heat's effect on soil PH, microorganisms and a lack of greenery production, among other things.

Summary of Gas Flaring

Flaring is a major problem in oil-producing areas when the infrastructure needed for an ideal production and use of the natural gas generated is lacking. Oil firms used to burn off excess gas that escapes as a consequence of drilling. Throughout the Niger Delta, gas flares burn several story's high, frequently within a few hundred yards of settlements. Some flares, such as the one depicted below, have been blazing nonstop for more than 30 years.



Fig. 1 flaring of natural gas in the Niger Delta

This is an aged-long tradition that is motivated by a number of factors, including economics and market constraints and absence of appropriate decree or regulation. State authorities often prohibit venting, which is the direct discharge of natural gas into the atmosphere.

The subject has been a difficult topic that continues to be debated across the world, particularly in nations with common flaring practice. References (Emam 2015; Ojjiagwo and Nwabueze 2016) reasoned that flaring was proposed because it is thought to be the most cost-effective way of short-term natural gas disposal. It is establish that it is done with either vertical or horizontal flare stack (Ochuko 2015).

A substantial origin of greenhouse gases and some other pollutants increased ambient temperature, and a vast region of inhaled pollution. Furthermore, instead of outright flaring, there are two choices for gas use: The first is the use of gas for domestic and commercial purposes, which demands the purchase of liquefaction and transportation equipment, and re-injection for improved oil recovery is the second option. Gas flaring is not human-friendly since it harms natural ecological systems and results in a significant loss of lives and income.

The Niger Delta Basin

Geographically, the Niger Delta is found near the southernmost tip end of a vast rift system that stretches from the present day Atlantic Ocean to the Mediterranean (Selley and van der Spuy 2016). It's one of the most prolific Paleogene-Neogene deltas on the planet, contributing around 5% of worldwide hydrocarbon output (Ajaegwu et al. 2014). The on-delta fluvial Benin Formation, Agbada Formation delta front sands and muds, and over-pressured slope muds of the Akata formation are all dichronous facies of the Niger Delta. Sedimentation of the deep-water underwater channel and fan sands prograded (Selley and van der Spuy 2016; Ogbe 2020). The origin of the rocks behind the generation of hydrocarbons in the region has been a matter of contention. The challenge involving identifying rock origin intervals cogent enough to produce the massive quantity of trapped crude has spurred this controversy. Only signs of putative rock origin have been made public so far (Bustin 1988).

The source rocks of the delta are mostly made up of terrigenous organic materials, and they date from the middle Eocene to the Pliocene epochs (Haack et al. 2000). Light waxy oils or gas are produced by these source rocks. As a consequence, the organic facies' gas-prone end-member was deposited in an anoxic depositional environment with poor organic material preservation (Haack et al. 2000). Oil-prone organic facies, on the other hand, were deposited in less toxic depositional settings, which allowed for greater preservation of terrigenous organic matter (Haack et al. 2000). Variations in the concentration of Components of organic materials that contribute to the kerogen of richer source facies are most likely to blame (Bustin 1988; Haack et al. 2000).

The Northern Delta, Greater Ughelli, Central Swamp, Coastal Swamp, and offshore depobelts are the five depobelts of the Niger Delta basin (Fig. 2). Every depobelt contains source rocks, which are responsible for hydrocarbon

production. In the Niger delta basin, the Northern Delta depobelt is an important petroleum province. According to (Oluwajana et al), oil found in the Northern Delta depobelt might be due to Eocene source facies (2017). The Eocene source rock has a VR0 of 0.42–1.17_o, indicating that it is thermally immature to mature. The TOC concentration of the Greater Ughelli depobelt's Upper Oligocene shale facies varies from 1.7 to 31.8 wt%, suggesting that the source rock is good to exceptional (Oluwajana 2018a; b).

The deeply buried upper Oligocene source facies is thought to have reached the primary oil opening during the Neogene, and might perhaps have provided some hydrocarbon to the interbedded Agbada sandstones of the Niger Delta Basin's Greater Ughelli depobelt (Oluwajana 2018a,2018b). The organic-clean and gas-prone Type III/IV kerogen that dominates the Miocene source rocks of the Coastal Swamp depobelt would have contributed to the Niger delta basin's oil deposit with a little input from oil and gas-prone mixed Type II/III kerogen (Oluwajana 2019). With a transformation ratio of less than 1%, late Miocene-Early Pliocene source rock reached the early oil production opening in the course of Miocene epoch, indicating that not enough hydrocarbons were evacuated to neighbouring reservoirs (Oluwajana, 2018b).

According to (Ekweozor 2004). The anoxic sediments from the Cenomanian–Turonian period reached the oil window just before or during the Santonian tectonics, but the deep offshore layers under the Niger Delta, where the Paleogene-Neogene overburden is greatly thinned, should have produced large volumes of liquid petroleum more recently, leading to massive oil pools in the Niger delta basin.

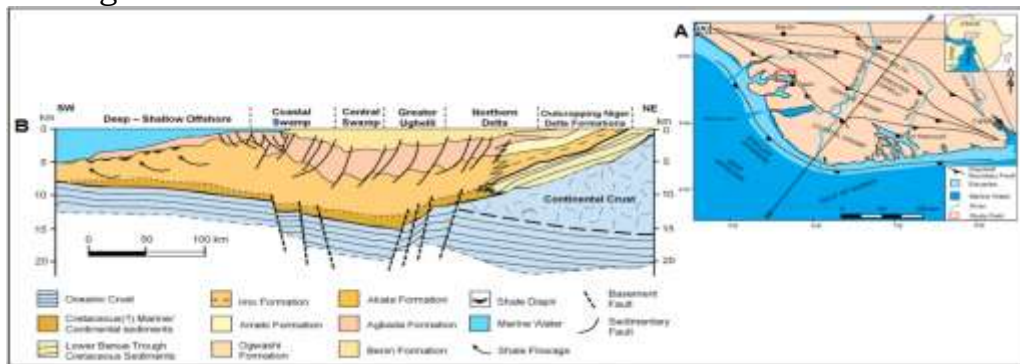


Fig. 2 A Niger Delta's simplified geological setting map for the area, displaying several depobelts.

B The location of the numerous deponents, as well as the three anachronous lithostratigraphic formations and related depositional processes, are shown in a schematic stratigraphic dissection of the Cenozoic Niger Delta Basin (Ogbe 2020).

Gas Flaring Composition

In most cases, the gas flared will be made up of a variety of gases. The composition will be determined by the gas supply for the flare system. The bulk of the gases released during oil and gas production are natural gas. Predominantly, the gas consists of methane (CH₄), with little volume of ethane

and other hydrocarbons, as well as inert gases such as N_2 and CO_2 . Hydrocarbons and, in rare situations, H_2 are often found in gas expelled out of refineries and other industrial plants. On the contrary, landfill gas, biogas, and digester gas are a mixture of CH_4 and CO_2 with trace amounts of other inert gases. Because gas flaring has no standard composition, it is essential to construct a group of gas flaring based on the gas's true properties.

The heat transmission capacity of the gas, as well as the efficacy of the flow meters measurement, will change as the gas composition changes. Table 1 shows the waste gas components of a typical plant. (Peterson et al 2007).

Table: 1. Natural gas-waste composition for a conventional plant

Gas flaring constituents		Gas composition (%)		
Gas flaring				
Max		Min		Average
Methane	CH_4	7.17	82.0	43.6
Ethane	C_2H_6	0.55	13.1	3.66
Propane	C_3H_6	2.04	64.2	20.3
n-Butane	C_4H_{10}	0.199	28.3	2.78
Isobutane	C_4H_{10}	1.33	57.6	14.3
n-Pentane	C_5H_{12}	0.008	3.39	0.266
Isopentane	C_5H_{12}	0.096	4.71	0.530
neo-Pentane	C_5H_{12}	0.000	0.342	0.017
n-Hexane	C_6H_{14}	0.026	3.53	0.635
Ethylene	C_2H_4	0.081	3.20	1.05
Propylene	C_3H_6	0.000	42.5	2.73
I-Butene	C_4H_8	0.000	14.7	0.696
Carbon monoxide	CO	0.000	0.932	0.186
Carbon dioxide	CO_2	0.023	2.85	0.713
Hydrogen sulfide	H_2S	0.000	3.80	0.256
Hydrogen	H_2	0.000	37.6	5.54
Oxygen	O_2	0.019	5.43	0.357
Nitrogen	N_2	0.073	32.2	1.30
Water	H_2O	0.000	14.7	1.14

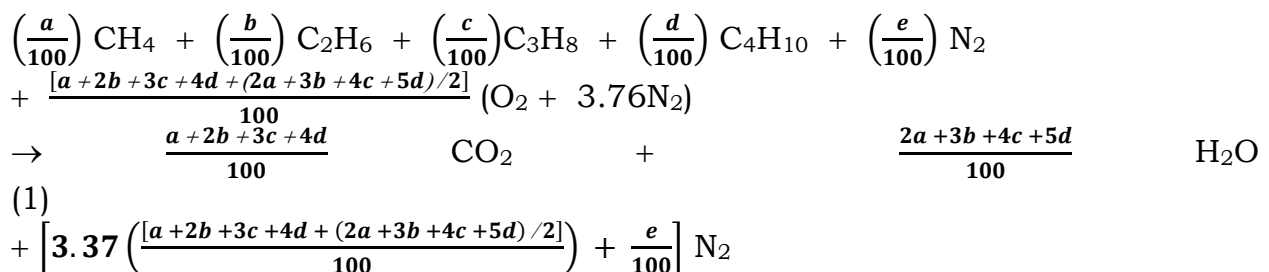
The usefulness of gas is mostly determined by its ability to heat. Flue gases composition is essential for identifying its economic worth plus matching it to an appropriate method or disposal. The gas H_2S concentration, for example, is a critical concern for transit in the upstream pipeline network. If a gas contains 10 mol/kmol H_2S or higher, it is regarded as sour (Johnson and Coderre 2012).

Information Gathering

The information needed for this inquiry (volume of gas flared in the Alpha field) was gathered during a nine-year period) in the Alpha Field, a Nigerian oil field in the Niger Delta area. It contains two oil fields, although most of the research is focused on one of them. Well pressures, velocity of discharge, flame height, and ambient temperature, as well as outlet temperature, gas composition, operating stack temperature, and stack height were gathered via corporate log sheets, key personnel interviews, email communication, and field visits.

Combustion Examination

By definition, combustion is the fast decomposition by oxidation of hydrocarbon elements (fuel) that produces energy and combustion substances. There were several relational equations showing combustion encountered. Nevertheless, from (Nwanya 2011), the combustion equation stated below is for 1 kmol of a gas stream with volumetric compositions, CH₄—a %, C₂H₆—b %, C₃H₈—c %, C₄H₁₀—d %, and N₂—e %:



With the knowledge of natural gas composition, we may calculate the ratio of the gas's carbon-to-hydrogen ratio as a whole using Equation (1)

- **Carbon (IV) Oxide Estimation**

The equation by (Nwanya 2011) is used to determine carbon (IV) Oxide and water vapour concentrations in the atmosphere and it's stated as:

$$\text{MASSCO}_2 = \frac{M_{\text{flared gas}}}{MM_{\text{fuel}}} \times MM_{\text{CO}_2} \quad (\text{kg}) \quad (2)$$

Where,

MASSCO₂ is the mass of carbon (IV) oxide, MM_{fuel} is the molecular mass of gaseous fuel, MMCO₂ is the molecular mass of CO₂ and M_{flared gas} depicts mass of the flared gas (kg).

Equation (2) was utilized to compare the percentage correlation found in this study to that suggested by (Nwanya 2011).

- **Adiabatic Flame Temperature (AFT)**

The greatest temperature by theory obtained, assume exergy is not lost to the surrounding, via combustion products (flue gases) are referred to as

adiabatic flame temperature (Moran et al. 2011). The following equations are used to assess it:

$$Q = \sum H^c = H_P - H_R \quad (3)$$

Where the possible is adiabati

$$H_P = H_R \quad (4)$$

Where:

$$H_P = \sum_e^P n_e (\bar{h}_{of} + \bar{h} + \bar{h}_o)_e \quad (5)$$

$$H_P = \sum_e^R n_i (\bar{h}_{of} + \bar{h} + \bar{h}_o)_i \quad (6)$$

Q denotes heat transfer, \bar{h}_{of} represents enthalpy of formation n_e & n_i are respectively amount of moles of products and that of reactants. R and P represent products variables and reactants respectively.

Again, $\bar{h} - \bar{h}_o = \bar{\Delta}h$, is the enthalpy difference between a reference temperature and a given temperature, which is generally 298 k (25°C), and information are obtained from the thermodynamic data tables of Jadranski naftovod (JANAF).

- **The Exergy Postulation**

When a system interacts with a specific reference environment, its exergy (E_x), otherwise called availability, is the greatest and possible theoretical research (Hart 2021) based on thermodynamics' first two rules. Exergies are divided into two categories, thermomechanical exergy (physical exergy) and chemical exergy are the two types of exergies.

- **Physical Exergy or Thermo-Mechanical**

The difference in temperature and pressure between the flowing matter and the surrounding environment is represented by the thermo-mechanical (physical) exergy (Moran et al. 2011) and is calculated as follows:

$$e_{x, TM} = E_{x, nonflow} + E_{x, flow} \quad (7)$$

$$e_{x, TM} = (U - U_o) + P_o(V - V_o) - T_o(S - S_o) + \frac{1}{2} mc^2 + mgz + (P - P_o)V \quad (8)$$

Where,

$E_{x, nonflow}$ denotes the non-flow exergy, whereas $E_{x, flow}$ is flow exergy; P_o is the pressure at the surrounding (kpa)

All properties will be specific after diving Equation (8) by mass, and the next equation becomes:

$$e_{x, TM} = (u + Pv) - (u_o - P_o v_o) - T_o(S - S_o) + \frac{1}{2} c^2 + gz$$

$$e_{x, TM} = (h - h_o) - T_o(S - S_o) + \frac{1}{2} c^2 + gh \text{ (kJ/kg)} \quad (9)$$

Since both potential and kinetic energy expressions are relatively small as compared to those of entropy & enthalpy, we ignore them:

$$e_{x, TM} = (h - h_o) - T_o(S - S_o) \quad (10)$$

where

h is the system's enthalpy as a whole; h_o is the enthalpy of the system's whole surroundings; S_o is the specific entropy of the system surroundings (kJ/kg K); S is the system's specific entropy; T_o is for reference temperature (K) of surroundings.

- **Chemical Exergy**

The greatest work available by establishing chemical equilibrium in a system with a constant temperature and pressure reference environment is known as chemical exergy. It's assessed using the following criteria:

$$e_{x, ch} = [\bar{g}_F + \left(a + \frac{b}{4}\right) \bar{g}_{O_2} - a\bar{g}_{CO_2} - \frac{b}{2} \bar{g}_{H_2O}] (T_o, P_o) + RT_o \ln \left[\frac{(y^e_{O_2})^{a+b/4}}{(y^e_{CO_2})^a (y^e_{H_2O})^{b/2}} \right] \quad (11)$$

Here, R is constant of universal gas (kJ/kmol K); y^e is the mole fractions of environmental composition; \bar{g} is component of the molar Gibbs function derived using conventional thermo-mechanical characteristics tables (Moran et al. 2011).

Calculation of Total Specific Energy

The sum of specific thermo-mechanical and chemical exergy equals total specific exergy as follows:

$$e_{x, T} = e_{x, TM} + e_{x, ch} \quad (12)$$

$$e_{x, T} = (h - h_o) - T_o(S - S_o) + \left[\bar{g}_F + \left(a + \frac{b}{4}\right) \bar{g}_{O_2} - a\bar{g}_{CO_2} - \frac{b}{2} \bar{g}_{H_2O}\right] (T_o, P_o) + RT_o \ln \left[\frac{(y^e_{O_2})^{a+b/4}}{(y^e_{CO_2})^a (y^e_{H_2O})^{b/2}} \right] \quad (13)$$

The Absolute Energy ($E_{X, T}$)

Sum exergy is calculated as: $E_{X, T} = \text{indicates mass of gas stream } (m) \times e_{x, T}$

$$M \left[(h - h_o) - T_o(S - S_o) + \left[\bar{g}_F + \left(a + \frac{b}{4}\right) \bar{g}_{O_2} - a\bar{g}_{CO_2} - \frac{b}{2} \bar{g}_{H_2O}\right] (T_o, P_o) + RT_o \ln \left[\frac{(y^e_{O_2})^{a+b/4}}{(y^e_{CO_2})^a (y^e_{H_2O})^{b/2}} \right] \right] (\text{kg}) \quad (14)$$

- **Radiation and Heat Flux Density**

The flow of heat energy per unit area per unit time is known as heat flux. According to the Stefan-Boltzmann equation, the radiant's energy rate of transmission is:

$$\text{Heat flux } Q = \sigma \varepsilon T^4 \quad (15)$$

Here, ε is the emissivity of the source; Q I – heat flux (W/m²); T is the temperature (K); σ denotes constant of Stefan-Boltzmann with (5.67 x 10⁻⁸ W/m²).

Results and Discussion

Table 2 shows the correlation between gas compositions on a year-by-year basis.

• Combustion Analysis

Here is some helpful hypothesis:

- Flow is uniform
- Water produces vapour at the product side
- The fuel was 25°C and 1 atm when it reached the flare stack, and the air was 27°C.

For 1 kmol of fuel, replacing values in Equation (1) and, we get: [during the first year, 2010] with $a = 93.9$, $b = 3.6$, $c = 1.3$, $d = 1.2$ and $e = 0$

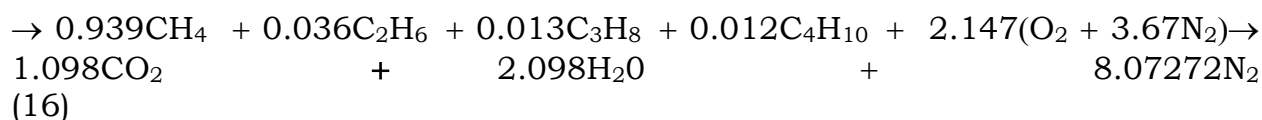
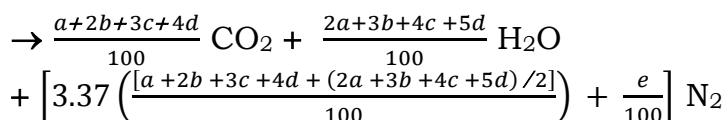
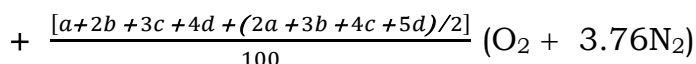
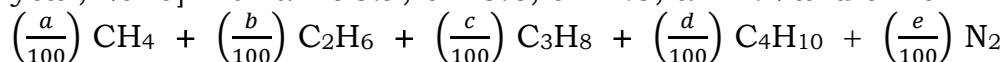


Table 2. Percentage of hydrocarbons flared by volume at the field under investigation – Alpha-Field

Natural gas sample	Methane(CH ₄) % = a	Ethane(C ₂ H ₆) % = b	Propane(C ₃ H ₈) % = c	Butane(C ₄ H ₁₀) % = d	Other incombustible s = e
A (2010)	93.90	3.60	1.30	1.20	0.00
B (2011)	91.35	4.00	2.8	1.22	0.63
C (2012)	90.43	4.50	3.40	0.70	0.97
D (2013)	87.50	5.74	3.90	1.62	1.21
E (2014)	85.60	7.40	4.50	1.30	1.20
F (2015)	83.00	7.9	5.00	2.20	1.90
G (2016)	79.70	8.50	4.80	2.50	4.50
H (2017)	78.71	11.19	4.25	2.85	2.12
I (2018)	78.74	11.77	5.97	1.40	2.14

Alpha field data log sheet is the source of this information (2018).

The coefficient of CO₂ on the product side of the combustion equation = 1.098 represents the number of carbon atoms, whereas that of hydrogen atoms is represented by the coefficient of H₂O × 2 = 2.098 × 2 = 4.196, as illustrated above. For this gas combination, the fundamental aggregated fuel is C_{1.098} H_{4.196}. As a result, the following stoichiometric equation emerges:

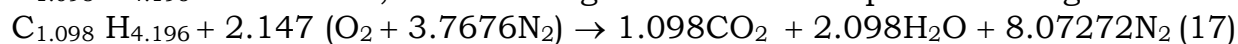


Table 3 shows the properties of natural gas combustion. The year-to-year sample of natural gas is shown in column one and the combined fuel content is in column two. As year advances, components with lighter weight become less

prevalent, whereas heavier components grow more prevalent. Nitrogen, CO₂, H₂O and the quantity of moles of stoichiometric air are also shown in the other columns.

• **Water vapour (H₂O) Production Analysis and CO₂ for the First Year (2010)**

According to the findings, 1m³ of fuel burnt in air produced 1.098 m³ and 2.098 m³ of CO₂ and water vapour respectively. Volume of flared gases was proportionately taken from Table 4 to determine the volumes of flue gases, as shown below: For the year 2010, the flare volume was 75,399,656.65m³. CO₂ emissions per year = 1.098 x 75,399,656.65 = 82,788,823.0017m³. Yearly H₂O production = 2.098 x 75,399,656.65= 158,188,479.6517m³. It also displays shows results of the aforesaid examination, which were acquired using MATLAB computer codes. See Table 4.

Table 3. Gas samples, quantity of air, fuel aggregates and amount of flue gases produced after burning

Natural Gas sample	Carbon-Hydrogen fuel content	Amount of air per kmol of fuel	Amount of CO ₂ produced per kmol	Amount of H ₂ O per kmol of fuel	Amount of N ₂ per kmol of fuel
A (2010)	C1.0980H4.1960	2.1470	1.098	2.0980	8.0727
B (2011)	C1.1263H4.2400	2.1912	1.1263	2.1200	8.2254
C (2012)	C1.1244H4.2296	2.1914	1.1244	2.1148	8.2132
D (2013)	C1.1722H4.3200	2.2644	1.1722	2.1600	8.4805
E (2014)	C1.1910H4.3580	2.2925	1.1910	2.1790	8.5867
F (2015)	C1.2260H4.4140	2.3485	1.2260	2.2070	8.7779
G (2016)	C1.1230H4.4400	2.3960	1.1230	2.2200	8.9179
H (2015)	C1.2578H4.4730	2.3974	1.2578	2.2365	8.9552
I (2016)	C1.1278H4.4730	2.3974	1.1278	2.2365	8.9552

Table 4. The amount of flare for the time period under consideration

Year	Production volumes m ³	Flare volumes m ³	Percentage of gas flared %	Quantity of CO ₂ (m ³)	Quantity of H ₂ O (m ³)
2010	169,668,539.73	75,399,656.65	44.44	82,788,823.0017	158,188,479.6517
2011	414,918,078.66	85,727,135.76	20.66	96,554,469.6276	181,741,527.8112

2012	355,971,341.25	97,458,655.39	27.38	109,582,512.1205	206,105,564.4188
2013	313,273,834.34	54,456,815.78	17.37	63,834,279.4573	117,626,722.0848
2014	128,155,262.21	59,469,427.36	46.40	70,828,087.9858	129,583,882.2174
2015	229,335,870.54	48,943,657.25	21.34	60,004,923.7885	108,018,651.5507
2016	66,656,401.91	31,132,508.91	46.71	3,517,807.5059	6,954,169.7802
2017	80,526,209.82	37,847,318.61	46.99	47,604,357.3476	84,645,528.0713
2018	111,564,578.95	50,588,818.23	45.34	47,604,357.3476	84,645,528.0713
TOTAL	1,870,070,117.41	541,023,993.9		582,319,618.2	1,077,510,054.31

• Carbon (IV) Oxide Estimation for Comparison

Recall the equation $MASSCO_2 = M_{flared\ gas} \times MMCO_2$, verification of the CO₂ quantity stated by (Nwanya 2011).

$$M_{flared\ gas} = \frac{MM_{fuel}}{MMCO_2} \times MASSCO_2$$

$M_{flared\ gas} = 59791927.7266 \text{ kg/year}; MMCO_2 = 44\text{g/mol}; MM_{fuel} = 17.372$

$$\text{After substitution, we derive: } MASSCO_2 = \frac{59791927.7266\text{kg/year} \times 44 \text{ g/mol}}{17.372} = 151441677.41\text{k}$$

Remember density of CO₂ = 1.98kg/m³

$$\text{So, density } (\rho) = \frac{\text{Mass}}{\text{Volume}} = \frac{m}{V}$$

$$\text{Volume} = \frac{151441677.41}{1.98} = 76485695.661 \text{ m}^3 / \text{year}$$

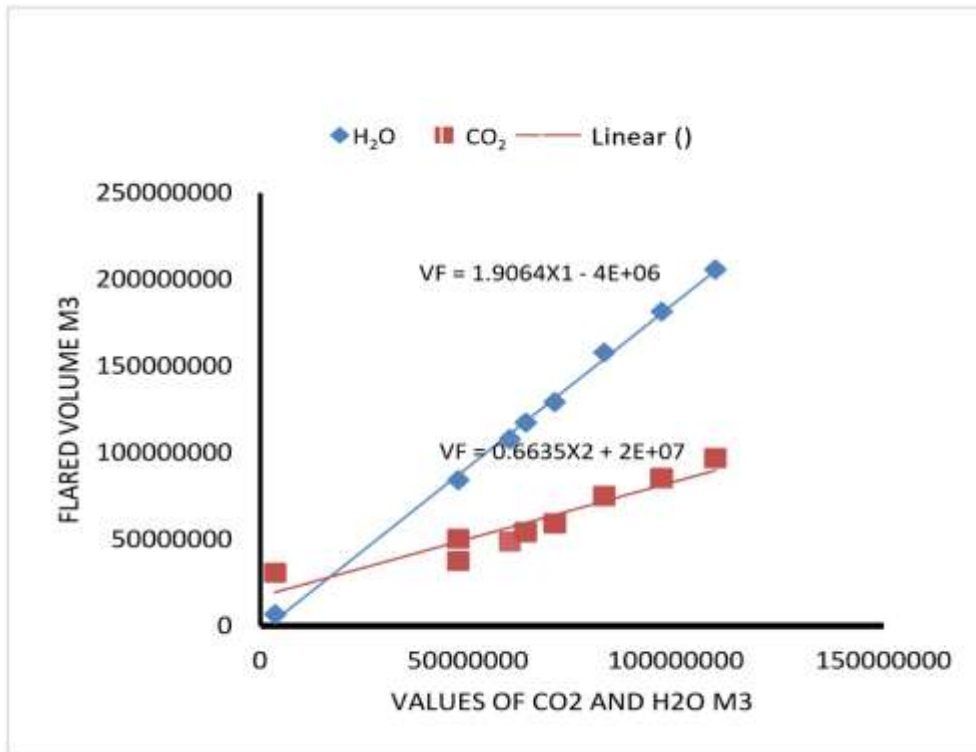
This study's proportional correlation with (Nwanya 2011) is: percentage correlation = $76485695.661 / 82788823.0017 = 0.923864 = 92.28\%$

Table 4 shows annual production volumes with flared composition, water vapour, the amount of carbon (IV) oxide for each year. According to analyses, total natural gas output was projected as 1,870,070,117.41 standard cubic meters for the nine-year period, with 541,023,993.9 standard cubic meters, resulting in CO₂ emissions of 582,319,618.2 (≈1.046 MMt) and water vapour emissions of 1,077,510,054.31 (2.054 MMt). According to another research, transitory losses released around 14,960,560.91 standard cubic meters of methane into the atmosphere.

Figure 3 and the acquired findings reveal that a linear fluctuation exists (i.e, CO₂ volume grows with flared amount), and the true alike for water vapour. The lines sharp slope also shows that water vapour effluent has about twice

the amount of carbon (IV) oxide discharge. In addition, flaring accounted for between 27% and 40% generated in total.

Figure 3. Variation in CO₂ and H₂O as a function flared volume



First Year study of Adiabatic Flame Temperature AFT (2010)

Recall Equation (2): $H_R = \sum_R n_i (\bar{h}_f + \bar{\Delta}_h)_i = 0.939(\bar{h}_{of} + \bar{\Delta}_h)CH_4 + 0.036(\bar{h}_{of} + \bar{\Delta}_h)C_2H_6 + 0.013(\bar{h}_{of} + \bar{\Delta}_h)C_3H_8 + 0.012(\bar{h}_{of} + \bar{\Delta}_h)C_4H_{10} + 2.147(\bar{h}_{of} + \bar{\Delta}_h)O_2 + 8.07272(\bar{h}_{of} + \bar{\Delta}_h)N_2$

Here, diatomic gases denoted by \bar{h}_o zero, $\bar{\Delta}_h$ denotes fuel and is also zero at 25°C.

This result becomes: $H_R = 0.939(\bar{h}_{of})CH_4 + 0.036(\bar{h}_{of})C_2H_6 + 0.013(\bar{h}_{of})C_3H_8 + 0.012(\bar{h}_{of})C_4H_{10} + 2.147(\bar{h}_{of})O_2 + 8.07272(\bar{h}_{of})N_2$

We get: (Moran et al. 2011) by substituting values from known standard thermodynamic tables:

$$H_R = 0.939 (-74873) + 0.036 (-84667) + 0.013(-103874) + 0.012 (-126148) + 2.147(54) + 8.07272(54)$$

$$H_R = -75666.03212 \text{ kJmol.} \quad (18)$$

Similarly, we have the following products:

$$H_P = \sum_P n_e (\bar{h}_{of} + \bar{\Delta}_h)_i$$

$$\begin{aligned}
 &= 1.098(\bar{h}_{o_f} + \bar{\Delta}_h)\text{O}_2 + 2.098(\bar{h}_{o_f} + \bar{\Delta}_h)\text{H}_2\text{O} + 8.07272(\bar{h}_{o_f} + \bar{\Delta}_h)\text{N}_2 \quad H_P = \\
 &1.098(-393522) + 1.098(\bar{\Delta}_h)\text{CO}_2 + 2.098(-241827) + 2.098(\bar{\Delta}_h)\text{H}_2\text{O} + \\
 &8.07272(\bar{\Delta}_h)\text{N}_2 = -938440.022 + 1.098(\bar{\Delta}_h)\text{CO}_2 + 2.098(\bar{\Delta}_h)\text{H}_2\text{O} + \\
 &8.07272(\bar{\Delta}_h)\text{N}_2 \qquad \qquad \qquad (19)
 \end{aligned}$$

Table 5 was created using standard lists of thermo-mechanical properties and iterative thermodynamics of various compounds (Moran et al. 2011). Interpolation is done in a linear fashion.

$$\frac{X - 2300}{2400 - 2300} = \frac{863774.16988 - 846590.42}{893862.094 - 846590.42}$$

$$X = AFT = 2336.351\text{K}(2063.351^\circ\text{C})$$

The adiabatic flame temperature is determined in this way, and additional variables are obtained using MATLAB algorithms and shown in the Figure 3. Same Figure shows that natural gas quality declined from 2010 to 2018, as seen by the graph’s profile, which shows reduction in adiabatic flame temperature. Apart from 2011 and 2013, adiabatic flame temperature has been steadily decreasing.

• **Heat Flux Calculation (Thermal Pollution Rate)**

The thermal pollution rate may be computed using the assessed adiabatic Flame temperature:

$$\begin{aligned}
 Q &= \sigma \varepsilon T^4 \\
 &= 5.67 \times 10^{-8} \text{W/m}^2\text{K}^4 \times 1 \times (2336.351)\text{K}^4 \\
 &= 1.63380 \times 10^6 \text{W/m}^2
 \end{aligned}$$

Figure 4 expresses thus, other heat flow values were evaluated using the MATLAB tool:

Table 5. Maximum temperature at the flare stack's discharge as a function of gas composition.

Exhaust products	Temperatures	
	2300 K	2400 K
1.098 □ □ h □ CO ₂	120,418.76	127,135.224
2.098 □ □ h □ H ₂ O	185,242.91	196,381.129
8.07272 □ □ h □ N ₂	540,928.75	570,345.741
□ □ □ □ □ □ □ □	846,590.42	863,774.16988
		893,862.094

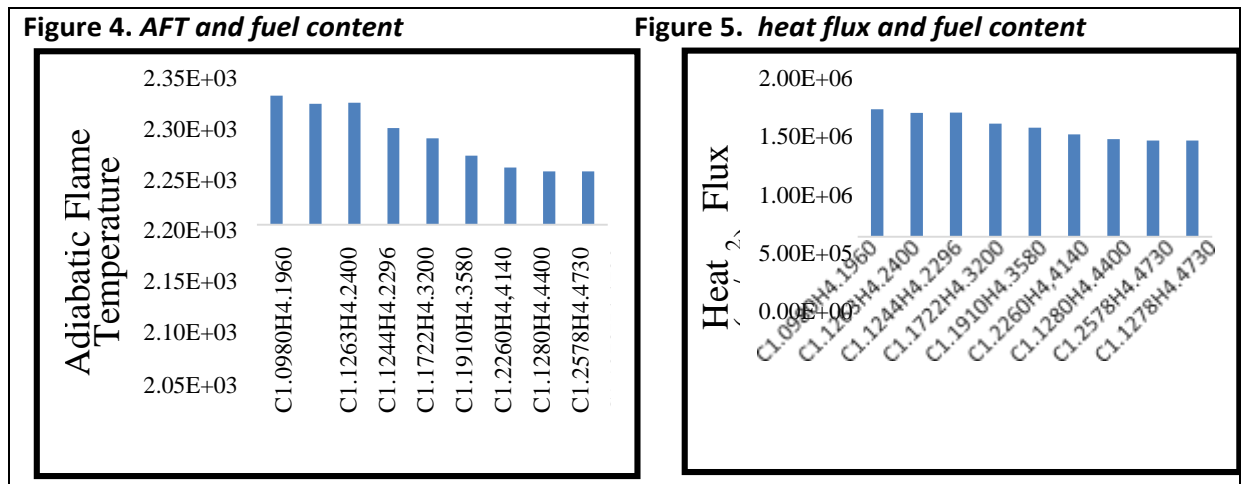


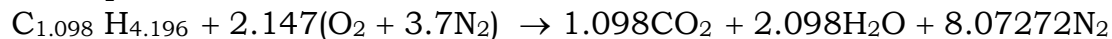
Figure 4. Shows that when the fuel ingredient grows heavier, the heat flow density decreases gradually. The flame tends to be hotter when lighter components are prevalent, which is consistent with adiabatic flame temperatures. This massive quantity of heat is to blame for low agricultural yields, a reduction in microorganisms, PH value of the soil and eroding conditions in corrugated sheets in flare zones.

• Computation of Chemical Exergy

The reference environmental model's molar analysis is as follows:

$$Y^e N_2 = 0.7567, Y^e O_2 = 0.2035, Y^e H_2O = 0.0303 \text{ and } Y^e CO_2 = 0.0003$$

The equation for balanced combustion is:



$$e_{x,ch} = [\bar{g}_F + \left(a + \frac{b}{4}\right) \bar{g}_{O_2} - a\bar{g}_{CO_2} - \frac{b}{2} \bar{g}_{H_2O}](T_0, P_0) + RT_0 \ln \left[\frac{(y^e_{O_2})^{a+b/4}}{(y^e_{CO_2})^a (y^e_{H_2O})^{b/2}} \right]$$

Applying the above equation to combustion products and provided environmental composition, as well as information from lists of thermo - chemical characteristics of chosen chemicals at 298K and 1atm (Moran et al 2011), we get:

$$e_{x,ch} = [-49026.89 + (2.147)(0) - 1.098(-390380) - 2.098(-228590)](T_0 - P_0)$$

$$+ (8.3144)(298) \ln \left[\frac{0.2035^{(2.147)}}{0.0303^{(2.098)} \times 0.0003^{(1.098)}} \right]$$

$$e_{x,ch} = [-49026.89 + 433029.24 + 479581.82] + [31814.8984]$$

$$e_{x,ch} = 863584.17 + 31814.8984$$

$$e_{x,ch} = 895399.2 \text{ (kJ/kmol)}$$

By dividing the fuel's molecular mass (17.379 kg/kmol), we obtain:

$$e_{x,ch} = \frac{895399.2}{17.379} = 51521.8998 \text{ (kJ/kg)}$$

• Computation of Thermo-Mechanical Exergy, $e_{x,TM}$

Flue gases thermo-mechanical contribution per kmol of fuel was calculated using ideal gas models.

$T = AFT = 2336.351K(2063.351^{\circ}C)$. Therefore, we get:

$$\begin{aligned} & \bar{h} - \bar{h}_o - T_o(\bar{s} - \bar{s}_o) \\ & = 1.098[\bar{h}(T) - \bar{h}(T_o) - T_o(\bar{s}^{\circ}(T) - \bar{s}_o^{\circ}(T_o)) - R\ln(y_{CO_2}, P / y^e_{CO_2}, P_o)]CO_2 \\ & \quad + 2.098[\bar{h}(T) - \bar{h}(T_o) - T_o(\bar{s}^{\circ}(T) - \bar{s}_o^{\circ}(T_o)) - R\ln(y_{H_2O}, P / y^e_{H_2O}, P_o)]H_2O \\ & \quad + 8.07272[\bar{h}(T) - \bar{h}(T_o) - T_o(\bar{s}^{\circ}(T) - \bar{s}_o^{\circ}(T_o)) - R\ln(y_{N_2}, P / y^e_{N_2}, P_o)]N_2 \end{aligned}$$

Reason that $P = P_o$, every term in logarithmic expression drop away, T represent the adiabatic flame temperature, \bar{h}_o & \bar{s}_o° are data at T_o . The thermo-mechanical contribution was computed using accepted established guidelines and parameters with different ideal gas properties (Moran et al. 2011):

$$\begin{aligned} & \bar{h} - \bar{h}_o - T_o(\bar{s} - \bar{s}_o) \\ & = 1.098[\bar{h}(T) - \bar{h}(T_o) - T_o(\bar{s}^{\circ}(T) - \bar{s}_o^{\circ}(T_o))]CO_2 \\ & \quad + 2.098[\bar{h}(T) - \bar{h}(T_o) - T_o(\bar{s}^{\circ}(T) - \bar{s}_o^{\circ}(T_o))]H_2O \\ & \quad + 8.07272[\bar{h}(T) - \bar{h}(T_o) - T_o(\bar{s}^{\circ}(T) - \bar{s}_o^{\circ}(T_o))]N_2 \\ & = 1.098[(121235.32 - 9364) - 298(318.642 - 213.685)]CO_2 \\ & \quad + 2.098[(100104.84 - 9904) - 298(272.659 - 188.720)]H_2O \\ & \quad + 8.07272[(76986.4 - 8669) - 298(257.59 - 191.502)]N_2 \end{aligned}$$

There,

$$\begin{aligned} \bar{h} - \bar{h}_o - T_o(\bar{s} - \bar{s}_o) & = 87889.4391 + 136762.364 + 392521.2854 \\ & = 617183.1 \text{ (kJ/kmol) quantity of fuel} \end{aligned}$$

To obtain the result (in kJ/kg), we divide by the fuel's molecular weight:

$$\bar{h} - \bar{h}_o - T_o(\bar{s} - \bar{s}_o) = \frac{617183.1(\text{kJ/kmol})}{17.379(\text{kg/kmol})} = 35513.153(\text{kJ/kg})$$

- **Summation and Calculation of Specific Exergy**

Equation (13) yields total exergy as seen below:

$$e_{x,T} = e_{x,TM} + e_{x,ch} 35513.153 + 51521.8999 = 87035.0529 \text{ (kJ/kg)}$$

- **Calculation of Total Exergy for the Time Period in Question**

Table 4 shows the overall volume of flare for the year 2010:

$$V_f = 75399656.65\text{m}^3/\text{year}$$

$$\rho_{ga} = 0.713\text{kg}/\text{m}^3$$

Mass (flared gas) = density \times volume (V_f) of the flared gas

$$= 0.713 \text{ kg}/\text{m}^3 \times 75399656.65\text{m}^3/\text{year}$$

$$= 53759955.19\text{kg}/\text{year}$$

So, exergy is total becomes,

$$E_{x,TI} = e_{x,T} \times 59791927.7266\text{kg}/\text{year}$$

$$= 4.6789 \text{ kg}/\text{year}$$

- **The Total Exergy's Electrical Equivalent**

For that year, projected total exergy's electrical equivalent is = $5.204 \times 10^{12} \times 0.0002778\text{kWh} = 1300761.361\text{kWh}$.

Table 6 shows the findings obtained using various gas composition density settings and the MATLAB software.

Table 6 shows that the greater the exergy, flaring also is greater (work potential). Exergy is highest in 2012, while the lowest exergy was in 2018. The table also reveals the total exergy under the duration as 3.6099×10^{13} kJ (36.099 TJ) corresponding to 1.0189×10^{10} kWh.

Table 6 Values of specific, total, and electric energy

Natural Gas sample	Specific exergy (kJ/Kg)	Total exergy (kJ) $\times 10^{12}$	Electrical energy (kWh) $\times 10^9$
A (2010)	85,561	4.6789	1.3007
B (2011)	87,141	5.5056	1.5295
C (2012)	86,966	6.2635	1.7399
D (2013)	88,561	3.7087	1.0303
E (2014)	88,974	4.1272	1.1465
F (2015)	90,908	3.5951	0.9987
G (2016)	91,892	2.3659	0.6572
H (2017)	90,974	2.9266	0.8930
I (2018)	90,974	2.9266	0.8930
Total	801,951	36.099	10.1888

Conclusions

Flared gases in the oil field are evaluated thermo-mechanically and environmentally. The study provided a solution to the research work's goals, which are:

1) To accomplish other aims, the temperatures of adiabatic flames were estimated correctly using thermodynamic expressions, insertion with MATLAB programme, suitably combustion expressions, variable gas compositions with iterative thermodynamics. The adiabatic flame temperatures for natural gas in this investigation averaged about 1965°C , which is consistent with gas turbine inlet temperatures.

The entire exergy was calculated using the concept of exergy and accompanying equations, and was found to be 3.6099×10^{13} kJ (36.099 TJ), equal to 1.0189×10 kWh of electrical energy. The study also found that between 27 and 40 percent of the gas produced in the field was flared throughout the examination period. Finally, while just one oil field provided such a large amount of energy, it is likely that massive quantities of energy were wasted in flaring gas from all of the oil fields in Nigeria's Niger Delta region, which might have been utilised to generate electricity or for other useful purposes.

2) Using basic thermodynamic combustion expressions (Kaushik and Singh 2013), the quantities of greenhouse gases, as well as their volumes, densities, and molar masses were calculated to be $582,319,618.1825 \text{ m}^3$ (≈ 1.046 million tonnes), $1,077,510,054.31 \text{ m}^3$ (≈ 2.0 million tonnes), plus $14,960,560.91 \text{ m}^3$,

respectively, which are all very harmful to the surrounding. This study exhibits a 92.3% association and quantity of carbon (IV) oxide which conforms to the equation.

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Nomenclature

P_o = Ambient pressure [kpa]

T_o = Ambient temperature [K]

a = No of moles of carbon [kmol]

b = No of moles of hydrogen [kmol]

AFT = Adiabatic flame temperature [K]

ΔH^C = Enthalpy of combustion [kJ/kg]

IT = Iterative thermodynamic

e_x = Specific Exergy[kJ/kg]

E_x = Total Exergy[kJ]

R = Universal gas constant [kJ/kmolK]

IOCs = International Oil Companies

\bar{g}_F = Gibb's function of formation[kJ/kmol]

E_p = Electrical Power generated [kWh]

\bar{h}_{o_f} = Molar enthalpy of formation [kJ/kmol]

y = Mole fraction

V_f = flared volume[m³]

TJ = Terajoules