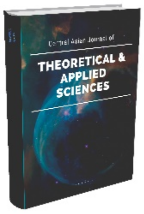

CENTRAL ASIAN JOURNAL OF THEORETICAL AND APPLIED SCIENCES

Volume: 03 Issue: 07 | Jul 2022 ISSN: 2660-5317
https://cajotas.centralasianstudies.org

Estimation of the Thermal Energy Release Rates from Gas Flare (A Case Study in the Niger Delta Region)

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Received 24th May 2022, Accepted 13th Jun 2022, Online 4th Jul 2022

Annotation: *The continuous flaring of gas and the attendant environmental hazards are well known and documented in the public domain. Thermal energy radiation, a direct effect of gas flaring, is due to chemical energy in natural gas molecules being converted to heat, light in the form of luminous and non-luminous flames, and roaring sound during the combustion of natural gas at the gas flare stack tip. The thermal energy released from the burning of gas is transferred to the immediate surroundings by convection, conduction, and radiation, with radiative heat transfer being the more dominant of the other modes of heat transfer. Thermal energy release rates from gas flare depend on several factors, which include the gas stream composition, the volume rates, the gross heating value (BTU), the efficiency, and soot formation. The paper will critically examine these factors and focus on the gas composition and gas volume rates as the major factors of interest to estimate the thermal energy release rates. The paper also outlined the quantitative estimation of the thermal energy release rates in simple and clear terms. The associated gas stream composition of the flare gas was obtained from the flow station. Other gas flare data obtained from the flow station's operational. The log book includes the average monthly gas volume flow rates, flare stack combustion efficiency, and the ambient and stacks flame temperature. The gross heating value (BTU/SCF) of the flare gas stream was evaluated from the gas composition and the standard BTU/SCF data for pure hydrocarbons (alkanes) gases, respectively. The calculated gross heating value of the gas stream was 1,876.72 BTU/ft3 at standard conditions. The thermal energy release rates were calculated from the average monthly volume flow rates of gas and the gross heating value of the flare gas stream. The estimated thermal energy released from the flared gas ranges from 43494.34KW to 313271.12KW from the months of January to December 2011, with an ambient temperature range of 318k to 328K (45oC to 55oC). The thermal energy release rates increase with an increase in the volume rates of gas flared. This leads to the unhealthy release of excess heat load into the environment, causing an excessive rise in the surrounding temperature above normal (180C-300C).*

Keywords: *Thermal Energy, Gas Flare, Gross Heating Value.*

1. Introduction

Gas flaring is the burning off of gas into the atmosphere (Osang *et al.* 2013). According to Nwaogu (2010), gas flaring is the unscientific burning of excess/stranded hydrocarbon gases gathered in an oil/gas production flow station. Abdulkareem (2011) reported that heat and obnoxious gases may contribute to environmental health problems in the Niger Delta region, and that free disposal of natural gas through flaring produces tremendous heat which is felt over an average of 0.5 kilometer radius, which causes thermal pollution.

Gas flaring and booming are the widely used methods of disposing of gases, often termed unwanted or hazardous. (Fawole *et al.,* 2020).

The combustion of gaseous hydrocarbons contained in natural gas is an exothermic process which results in the evolution of heat into the atmosphere (Abdulkareem *et al.* 2012).

Gas flaring activities can result in the production of some undesirable by-products, which include noise, smoke (soot), thermal radiation, light, and flue gases, such as SOx, NOx, and COx. Eweoya (2005).

Flaring is a high-temperature oxidation process used to burn off waste or stranded gases containing combustible components such as volatile organic compounds (VOCs), natural gas, or methane, CO, and hydrogen, John *et al.* (2019).

The dangers of thermal radiation from continuous gas flaring to human and environmental health cannot be overstated. Gas flaring is also associated with particulate emissions such as soot due to incomplete combustion. The inefficient combustion of gaseous hydrocarbon mixtures and the escape of unburnt gases cause greenhouse effects in the Niger-Delta Region.

Nigeria's gas flare is currently estimated to be 2 billion standard cubic feet per day, the highest so far in any member nation of OPEC.

The quantity of associated and non-associated gas flared in Nigeria is equivalent to the total annual power generation in the sub-Saharan region of Africa.

According to Ahmad (2021), the global gas flare rate has been estimated to be 150 billion cubic metres or 5.3 trillion standard cubic feet of associated gas being flared annually from the mid 1990s to 2020.

Jain *et al.* (2000) reported that methane, the major component of natural gas being flared, has an estimated global warming potential of 34 times higher than that of CO_2.

Emissions from gas flares account for 270 metric tons of CO_2 in 2017 (IEA, 2020).

Gas flare stacks with low efficiency may emit higher levels of unburned methane and other volatile organic compounds, as well as SOX, which pose a serious health risk (EPA, 2000).

According to the Department of Petroleum Resources (DPR), Nigeria's daily production of natural gas is put at 8 billion standard cubic feet (SCF). DPR gas utilization statistics further revealed that, out of 8 billion SCF of daily production, 39% goes to the NLNG plant, 31% for the gas reinjection programme, 16% of it is flared, and 14% is for domestic consumption.

The implication is that Nigeria's gas master plan is not fully implemented. Domestic gas utilization is grossly inadequate. Gas flaring accounts for 16% of the total gas produced daily Dung *et al*. (2008). The 16% of gas flared could have been used for power generation, petrochemicals, and chemical allied industries, hastening the realization of the gas flare out dream. The continuous flaring of gas has also been implicated in thermal pollution, amongst other things.

2. Thermal Radiation and Factors Affecting Thermal Energy Radiation from Gas Flares

2.1 Thermal Radiation

The mechanism of radiant energy transfer is not completely known. However, the associated phenomenon is explained in terms of dualistic theory Abdulkareem *et al*. (2012). This theory deals separately with the emission and reception of radiation and with its transmission, but it is emitted and received as a discrete particle called a photon according to Abdulkareem *et al*. (2012).

Eweoya (2005) reported that the heat released by combustion on the flare stack depends on the chemical composition of the flare gas stream. He also stated that the thermal radiation characteristics of a flame resulting from gas flaring of any hydrocarbon originate basically from two sources: flue (exhaust gas composition) and solid particles, usually coke or soot, burning in the flame. It is also important to note that not all of the heat generated from gas flare flame can be transferred by radiation.

Agbola *et al.* (2003) reported that, flaring of 1.8 billion standard cubic feet (SCF) of gas per day releases about 45.8 billion KW of heat into the atmosphere of the Niger Delta region.

Leahey *et al.* (1984) observed that, in gas flares, the heat released consists of sensible and radiation heat loss.

Schwartz and White (1996) showed that the fraction of heat radiation is the sum total characteristics of the flame that can be influenced by the following critical variables: gas composition, nature of flame, air to fuel mixing ratio. The forcing function of radiating gas flare flames is the sum of the heating values of the gas and gas flow rates, the thermal emission factors of component gases in the flame, and the discharge velocity. The radiant heat intensity of the gas flare flame depends on the rate of combustion and evolution of heat.

2.2 Factors Affecting Thermal Energy Radiation from Gas Flares

2.2.1 Composition of Gas and Gross Heating Value

The gross heating value of a gaseous mixture depends on the molecular composition of the gas. Kent's (1964) correlation provides a theoretical relationship between the fraction of heat radiated and the net heating value of gas. The correlation equation is expressed as follows:

$$f = 0.2\sqrt{\frac{H_c}{900}} \qquad (1.0)$$

where H_c= 50m + 100 for pure hydrocarbon gases.

$H_c = \sum_{i=1}^{n} ni\ H_{Ci}$ for gaseous hydrocarbon mixtures.

m = molecular weight.

H_c = net heating value of gas BTU/Ft^3

n = mole fraction of gas components

f = fraction of heat radiated

Gas composition to a greater extent determines the fraction of heat radiated from gas flaring.

2.2.2. A Gas Flare Flame Structure

Gas flare flame length (height) has a number of correlations. Hottel *et al*. (1949) correlation seemed to be outstanding and was adopted by API. Pohl *et al*. (1985) work showed that the flare head, the exit velocity, and the high heating value of the gas flared directly affect the structure of gas flare flames.

Pogni *et al.* (1976) and Delichatsois (1984) showed that flame heights correlated very closely with the heat release rate in laminar and turbulent flame regimes. Thus, the amount of heat radiated depends on the gas flare flame size.

2.2.3 The Formation of Soot and Hot Gases

Typically, about 80% or more of the radiated heat from luminous flames is emitted by soot, while about 20% of the radiated heat comes from hot gases such as ozone and unburned hydrocarbons. Thus, soot and hot gases in a gas flare enhance heat radiation.

2.2.4 Flare Stack Efficiency

Sawaragi *et al.* (1978) reported that the low combustion efficiency of Nigerian flare stacks (40–65%) results in a large proportion of unburned gas being. The incomplete combustion of gas also results in the formation of smoke particles, which enhances black body emission via the presence of soot in the flame.

2.2.5 The Temperature of the Flame

The extent to which heat is radiated from gas flaring depends on the gas flame temperature according to the point source flame model; the heat flux from gas flame is related to the gas flame temperature, ambient temperature, and the gas emissive factor. It is given by the expression:

$$k = 0.1713\left(\frac{Ts}{100}\right)^4 + \frac{0.21}{Eg(Ts-Ta)^{4/3}} \qquad (2.0)$$

where:

k is the radiant heat flux, KWM^{-2} from point source of gas flare stack

Ts = stack flame temperature $°c$

Ta = ambient temperature $°c$

Eg = gas emissivity factor

Thus the higher the gas flame temperature, the higher the thermal energy release rates to the surrounding.

2.2.6 Effect of Plume Rise

Plume rise is directly related to the dispersion of thermal energy and gaseous/particulate effluents over a long distance, depending on the effective plume height and cross wind velocity and other climatic factors. Effective plume rise enhances the heat dissipation from gas flare by radiation. As much as 55% of the heat of combustion of the flared gases is lost due to radiation, according to Leahey *et al.* (1984).

The expression for plume rise for buoyancy flux factor

$$\Delta H = 1.6F_d{}^{1/3}U^{-1}(10\square)2/3 \qquad (3.0)$$

$\Delta\square$ = plume rise or increase in stack height (m)

U= Wind speed m/s

h = Stack height (m)

F_d = Buoyancy flux factor = $3.7\text{x}10^{-5}\,Q_h$

$Q_\square$ = Heat emission or release rate from gas flare J/S

The effective plume height H is given by,

$$H = \square + \Delta\square \qquad (4.0)$$

Thus, plume rise is an effective process of thermal energy transport.

2.2.7 The Gas Flared Volume Flow Rates

The quantity of gas flared per unit time determines the quantity of heat released per unit time. Thus, increase in the volumetric rates of flow of gas being flared increases the combustion with a corresponding increase in thermal energy release rates.

The heat release rate from gas flare and volumetric flow rate is related as follows:

$$Q = VH \qquad (5.0)$$

where Q is the heat release rates in KW

V is the volume flow rate of gas m^3/s

H is the gross heating value of gas $KJ/^{m3}$

The full bright luminous flare gas flames in flow stations at night is as a result of large volumes of gas flared especially natural gas with substantial intermediate ends with high calorific value.

3. Materials and Method

The molecular composition of the gas stream was obtained from the flow station operational log book. The operational log book contains other data such as, average monthly gas volume flow rates from January to December, 2011, ambient temperature, ‚stack (flame) temperature, ‚flare stack efficiency, flare stack height and diameter, wind speed, and effluent (flue) gas velocity, respectively. The average gross heating value of the gas stream was calculated using the gas stream composition and standard gross heating (calorific) values of pure hydrocarbon (alkane) gases data from literature (see www.enegineeringtoolbox.com).

TABLE 1. MOLECULAR COMPOSITION OF THE FLARE GAS STREAM

Component	Weight	Mole (%)	Molecular Weight
CH_4	23.5	47.0	16.04
C_2H_6	16.8	18.0	30.04
C_3H_8	27.5	20.0	44.09
C_4H_{10}	9.1	5.0	58.12
C_5H_{12}	20.3	9.0	72.15
C_6+	2.8	1.0	88.84
	100.0	100.0	

Source: Flow station operational log book

Average Molecular Weight of Gas =32.06g/ mole

Specific Gravity (Air = 1.0000) =1.1070

TABLE 2. DATA ON THE STANDARD GROSS HEATING VALUE OF PURE HYDROCARBON GASES

Component	CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}	C_{6+}
Gross Heating value (BTU/ft^3)	1011	1783	2572	3225	3981	4667

3.1 Methodology

3.1.1 Determination of the Average Gross Heating Value of the Flare Gas Stream

Tables 1 and 2 are used to calculate the average gross heating value of the gas stream since the associated gas stream being flared is a mixture of hydrocarbon (alkane) gas components. The average gross heating value of the gas mixture is calculated by the summation of the product of each component's gross heating value and the corresponding mole fraction, respectively.

Let Y_1, Y_2, Y_3, $Y_4 \ldots Y_i$, be the mole fractions of each component in the gas stream.

Let H_1, H_2 H_3, $H_4 \ldots H_i$ be the corresponding heating value of each component in BTU/ft^3

Therefore, $H = Y_1H_1 + Y_2H_2 + Y_3H_3 + Y_4H_4 + \ldots Y_iH_i$ (6.0)

$H = \sum_1^n YiHi$ (7.0)

Table 3 shows the average gross heating value of the flare stream.

TABLE 3. CALCULATED AVERAGE GROSS/ft^3) HEATING VALUE OF FLARE GAS STREAM (BTU)

Component	Mole Fraction Y_i(1)	Gross Heating Value H_iBTU(2)	Average Gross Heating Value H(1x2)
CH_4	0.47	1011	475.17
C_2H_6	0.18	1783	320.94
C_3H_5	0.20	2572	514.40
C_4H_{10}	0.05	3225	161.25
C_5H_{12}	0.09	3981	358.29
C_6+	0.01	4667	46.67
$\sum$	1.00		1876.72 BTU/ft^3 69926.59 KJ/m^3

Source: Flow station operational log book

TABLE 4. FLOW STATION PROCESS PARAMETERS FROM OPERATIONAL LOG BOOK 2011 DATA

Month	Gas Volume Rate (m^3/s)	Discharge Effluent Velocity (m/s)	Wind Speed (m/s)	Ambient Temp (K) Ta	Stack Temp (K) Ts
January	1.174	14.0	1.5	320	1000
February	4.480	14.0	2.0	325	950
March	1.121	13.5	1.5	318	1100
April	1.137	12.5	1.0	319	1000
May	0.622	12.5	1.3	325	900
June	0.877	12.0	2.0	320	1100
July	0.947	12.0	1.5	328	1150
August	1.126	12.5	1.8	320	900
September	1.103	14.0	2.0	318	1080
October	1.071	14.0	2.5	320	1000
November	1.092	12.0	3.0	320	950
December	0.977	13.0	2.8	328	1100

Stack Height: 6.1m

Stack Diameter: 0.34m

Stack Efficiency 64%

3.2 Determination of Thermal Energy Release Rates from Gas Flare Data

The heat release rate is the rate at which heat energy from the combustion of flare gas is released from the flare. It is expressed in BTU/ hour or KJ/S (KW), (See, firenist.gov).

The rate of heat release is the quantity or volume of gas flowing into the flare stack that is burnt per unit time. This heat is transmitted into the surrounding area by radiation.

Let Q = heat release rate from flare (KW)

V= volume flow rate of gas (m^3/s)

H =Average gross heating value of gas KJ/m^3

Therefore, Q= V H from Equation (5.0)

Q is the quantity of heat released from the combustion of V volume of gas per second. The quantity, Q was determined using tables 3 and 4 Data respectively.

TABLE 5. COLUMN (3) SHOWS THE CALCULATED VALUES OF THERMAL ENERGY RELEASE RATES IN EACH MONTH OF 2011

Month	V(1) Gas Volume Rate (m^3/s)	Heating Value (KJ/m^3)H	Q (3) 1 x 2 Heat Energy Release Rates (KW)	Ambient (4) Temp (K) Ta	Stack (5) Temp (K) Ts
January	1.174	69926.59	82093.82	320	1000
February	4.480	69926.99	313271.12	325	950
March	1.121	69926.59	78387.71	318	1100
April	1.137	69926.59	79506.53	319	1000
May	0.622	69926.59	43494.34	325	900
June	0.877	69926.59	61325.62	320	1100
July	0.947	69926.59	66220.48	328	1150
August	1.126	69926.59	78737.34	320	900
September	1.103	69926.59	77129.03	318	1080
October	1.071	69926.59	74891.38	320	1000
November	1.092	69926.59	76359.84	320	950
December	0.977	69926.59	68318.28	328	1100

4. Results Discussion

The results in column three (3) of Table 5, shows the estimated thermal energy release rates from the months of January to December, 2011. The thermal energy release rate in the month of February was 313271.13 KW, the highest with a corresponding gas volume rate of 4.48m3/s.

The month of May, with the least gas volume rate of 0.622m3/s has the least thermal energy release rate of 43494.34 KW, respectively.

The stack (gas flame) temperature range is 900 K to 1150 K (627C to 877C) while the ambient temperature range is 318 k to 328 k (45C to 55C). The month of July recorded the highest flame temperature of 1150 k (877C) with an ambient temperature of 328 k (55^0C).

May and August have the lowest stack temperature of 900 K (627 C), while March and September have the lowest ambient temperature of 318 K (45 C) with relatively higher stack temperatures.

The implication of the result is that continuous flaring of gas in the Niger-Delta region of Nigeria places a high thermal radiation risk factor on the lives of the people of the region. The result further shows that there is a high degree of thermal pollution caused by gas flaring, which has raised the surrounding temperature above the normal limit of 293–302K, 20C–29C (Canadian Centre for Occupational Health and Safety 1997–2014). The enormous quantity of heat released into the atmosphere by gas flare stations in the range of (43.5 MW-313.3 MW) has significantly raised the surrounding temperature above the normal level by more than 18 to 26C. This will no doubt negatively impact human and ecological resources in communities located around the gas flare station.

The excess heat load released into the environment is far above the DPR recommended safe limit as observed by Obi et al. (2015) in their studies.

5. Conclusion

The calculated value of the heat release rate to the environment from January to December 2011 averaged 91.6 MW. This shows there is a high level of heat released into the environment around the flare site.

Obi *et al.* (2015) reported that the natural equilibrium within the Ogbe-Ebgbema-Ndoni area under study has been altered in their study on the thermal effects of gas flaring activities in the Niger Delta. This was as a result of a rise in temperature above the normal temperature of the environment. They concluded that this was as a result of excessive heat released from gas flaring activities. Scientific and economic activities have been negatively impacted.

There was a significant rise in the surrounding temperature throughout Jan-Dec of 2011. The associated gas stream channeled to the flare for wasteful burning should have been processed to recover the intermediate ends (c_3-c_5) for use as compressed natural gas liquids (Gasoline) and LPG as an alternative to boost the domestic supply of fuel.

The ends of c_1-c_2 can be used as fuel gas for thermal power plants for electricity generation. The heat load released to the environment is far in excess of the API/DPR recommended safe limit for an area of operation, which is 6.31 KJ/S per square meter. DPR should embark on regular monitoring of the thermal radiation load at different gas flare sites across the Niger-Delta upstream and downstream operational area.

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