Journal of King Saud University – Engineering Sciences (2017) 29, 178–182

King Saud University

Journal of King Saud University – Engineering Sciences

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ORIGINAL ARTICLE

Modelling emissions from natural gas flaring

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Received 22 June 2014; accepted 27 August 2015
Available online 3 September 2015

KEYWORDS

Modelling;
Emissions;
Natural gas;
Environmental degradation;
Gas flaring;
Combustion

Abstract The world today recognizes the significance of environmental sustainability to the development of nations. Hence, the role oil and gas industry plays in environmental degrading activities such as gas flaring is of global concern. This study presents material balance equations and predicts results for non-hydrocarbon emissions such as CO_2, CO, NO, NO_2, and SO_2 etc. from flaring (combustion) of 12 natural gas samples representing composition of natural gas of global origin. Gaseous emission estimates and pattern were modelled by coding material balance equations for six reaction types and combustion conditions with a computer program. On the average, anticipated gaseous emissions from flaring natural gas with an average annual global flaring rate 126 bcm per year (between 2000 and 2011) in million metric tonnes (mmt) are 560 mmt, 48 mmt, 91 mmt, 93 mmt and 50 mmt for CO_2, CO, NO, NO_2 and SO_2 respectively. This model predicted gaseous emissions based on the possible individual combustion types and conditions anticipated in gas flaring operation. It will assist in the effort by environmental agencies and all concerned to track and measure the extent of environmental pollution caused by gas flaring operations in the oil and gas industry.

1. Introduction

'Flare the gas, flare the environment,' a cliché one can quickly use to discourage gas flaring. Flaring has been described as a multibillion dollar waste and a local environmental catastrophe. However, it is still widely used as a disposal option for associated gas in oil production especially where there is inadequate infrastructure for utilization of this gas. This is because flaring minimizes venting and can also burn efficiently. Environmental issues of gas flaring are generally described in terms of efficiency and emissions (Gobo et al., 2009). Flaring can be inefficient especially with combustion being affected by ambient winds and several other factors leading to incomplete combustion. Incomplete combustion leads to formation of several products resulting from various reactions taking place. Li and Williams (1999), gave several reactions taking place in combustion of natural gas. During a combustion reaction, several intermediate products are formed, and eventually, most of them are converted to CO_2 and water. Some stable intermediate products and other by-products such as hydrocarbons, CO, H_2, NO, NO_2, SO_2 etc. will escape as emissions (Kahforoshan et al., 2008; AbdulKareem et al., 2009). The effect of thermal radiation emitted from flaring operation is also of great

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Peer review under responsibility of King Saud University.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.jksues.2015.08.001
1018-3639

concern, as there are limits to which the habitat can tolerate the fluxes released (Ismail and Fagbenle, 2009).

One of the challenges involved in addressing environmental aspects of flaring is determining how much emission is being released. Several methods exist for quantifying emissions, including direct measurement of sources and estimation techniques such as emission factors and engineering calculations. Direct measurement involves measuring actual emissions and collecting empirical data from a source or process. Emission factors are representative values that relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant, while engineering calculations refer to the estimation of emissions using engineering parameters (EPA, 2013). Some of these methods were reviewed in (Ismail and Umukoro, 2012). Marland and Rotty (1984), for example, estimated the amount of CO_2 emitted to the atmosphere from fossil-fuel burning, gas flaring, and cement production using Eq. (1).

$$CO_2i = (Pi)(FOi)(Ci) \tag{1}$$

where subscript i represents a particular fuel commodity, P represents the amount of fuel i that is consumed each year, FO is the fraction of P that is oxidized, C is the average carbon content for fuel i, and CO_2 is the resulting CO_2 emissions for fuel i expressed in mass of carbon. Global total CO_2 emission estimates are generated by using the above equation, where P represents production data from the United Nations Statistic Database for all primary solid, liquid, and gas fuels (Boden et al., 1995).

There has been continuous effort to improve on some of these methods. Estimation for example is unsure and uncertain as they are based on experiments in controlled environment and assumptions of certain factors. Also, some emission factors in use are questionable. The EPA for example, has no emission factor for flares and enclosed combustors for NOx, CO, SO_2 and some greenhouse gas (EPA, 2013). With predictive models and combustion analysis such as the one attempted here, better prediction of emissions that degrade our environment can be made in order to meet federal, state and local environmental regulations. This paper presents an attempt at a prediction of the emissions of CO, CO_2, NO, NO_2, and SO_2 from the flaring of associated natural gas.

2. Methodology

Emission from gas flares is predicted here by adopting mass balance equations for various flaring conditions as developed in Ismail and Umukoro (2016). The 6 reaction types and conditions are presented here in Eqs. (2)–(9). All conditions considered favour incomplete combustion. The chemical composition of flared gas (Table 1) and combustion efficiency (measure of how effective that flare is in converting all of the carbon in the fuel to CO_2) are central in the analysis.

I. **Reaction type 1**: Incomplete combustion of "sweet gas" without the formation of oxides of nitrogen (NOx) at temperature $T < 1200$ Kelvin (K).

$$\begin{aligned}&[C_xH_y + aCO_2 + jN_2] + b(O_2 + 3.76N_2) \rightarrow \\ &\eta xCO_2 + \eta \tfrac{y}{2}H_2O + (1-\eta)xCO + (1-\eta)\tfrac{y}{2}H_2 + dO_2 \\ &+ jN_2 + aCO_2 + 3.76bN_2\end{aligned} \tag{2}$$

where

$$d = \left[x\left(\frac{1}{2} - \frac{\eta}{2}\right) + y\left(\frac{1}{2} - \frac{\eta}{4}\right)\right] \tag{3}$$

'a' is the known stoichiometric coefficient for CO_2 in flare stream (Table 1).
'b' is the unknown stoichiometric coefficient for the amount of air involved in combustion.
'j' is the known stoichiometric coefficient for N_2 in flare stream (Table 1).
C_xH_y is the total hydrocarbon in the composition of Natural gas (Table 1) and
'd' is the unknown stoichiometric coefficient for the excess oxygen in product of combustion.
'η' is the combustion efficiency (mass based) expressed in terms of the stoichiometric coefficient.

II. **Reaction type 2**: Incomplete combustion of "sweet gas" with oxides of nitrogen (NO_x) formed as nitric oxide (NO) only. Reaction temperature (T) in kelvin is assumed to be $1200\ K \geq T \leq 1600\ K$.

Table 1 Natural gas composition in percentage moles/volume employed in the study.

S/N	Methane	Ethane	Propane	Butane	Pentane (C_5+)	N_2	CO_2	H_2S	Gas field	Origin
1	92.51	2.78	1.66	0.78	0.30	0.11	0.22	–	Soku	Nigeria
2	90.12	6.94	2.09	0.771	0.079	–	–	–	FS-2	Nigeria
3	81.3	2.9	0.4	0.1	0.1	14.3	0.9	–	Groningen	(NLD)
4	95.7	3.6	–	–	–	0.4	0.3	–	Frigg	(NOR)
5	83.7	6.8	2.1	0.8	0.4	5.8	0.2	–	Hassi R'Mel	Algeria
6	85.3	5.8	5.3	2.1	0.2	0.9	0.4	–	Urengoy	Russia
7	45.6	5.8	2.9	1.1	0.8	–	43.8	–	Kapumi	(NZL)
8	82	10	3.7	1.9	0.7	1.5	0.2	–	Maracalbo	(VEN)
9	69	3	0.9	0.5	0.5	1.5	9.3	15.3	Lacq	France
10	55.5	18	9.8	4.5	1.6	0.2	8.9	1.5	Uthmaniyah	(SAU)
11	74.3	14	5.8	2	0.9	2.9	–	0.1	Burgan	Kuwait
12	56.9	21.2	6	3.7	1.6		7.1	3.5	Kirkuk	(IRQ)

Source: Ismail and Umukoro (2016).