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ORIGINAL ARTICLE

Modelling combustion reactions for gas flaring and its resulting emissions

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Abstract Flaring of associated petroleum gas is an age long environmental concern which remains unabated. Flaring of gas maybe a very efficient combustion process especially steam/air assisted flare and more economical than utilization in some oil fields. However, it has serious implications for the environment. This study considered different reaction types and operating conditions for gas flaring. Six combustion equations were generated using the mass balance concept with varying air and combustion efficiency. These equations were coded with a computer program using 12 natural gas samples of different chemical composition and origin to predict the pattern of emission species from gas flaring. The effect of key parameters on the emission output is also shown. CO_2, CO, NO, NO_2 and SO_2 are the anticipated non-hydrocarbon emissions of environmental concern. Results show that the quantity and pattern of these chemical species depended on percentage excess/deficiency of stoichiometric air, natural gas type, reaction type, carbon mass content, impurities, combustion efficiency of the flare system etc. These emissions degrade the environment and human life, so knowing the emission types, pattern and flaring conditions that this study predicts is of paramount importance to governments, environmental agencies and the oil and gas industry.

1. Introduction

Despite the global campaign against the flaring of Associated Petroleum Gas (APG) during crude oil production and the resulting environmental degradation, gas flaring remains a major disposal option for unwanted APG. Flaring as a combustion process is believed to burn efficiently. Nevertheless, if gas must be flared, an accurate means must be provided to determine the volume of gas flared and the quantity of the resulting emissions (Ismail and Umukoro, 2012). Combustion of fossil fuels such as APG in flares results in the emission of greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide which cause global warming (EPA, 2008). Also, depending on the waste gas composition and other factors, the emissions of pollutants from flaring may consist of unburned fuel (e.g. methane and volatile organic compounds) and byproducts of the combustion process (e.g. Soot, CO_2, CO, NO, NO_2, and SO_2) which are of health and environmental concern (Abdulkareem, 2005; EPA, 2011; Kahforoshan et al., 2008; Manshaa et al., 2010; Villasenor et al., 2003; Wilk and Magdziarz, 2010). CO causes reduction

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in oxygen-carrying capacity of the blood, which may lead to death. SO_2 also has an adverse effect on health, vegetation and buildings. Uncontrolled oxides of nitrogen emission could be injurious to health. When NO_x reacts with the oxygen in the air, the result is ground-level ozone which has very negative effects on the respiratory system and can cause inflammation of the airways, lung cancer etc. In the environmental context, NO_x contributes to acid deposition, lower air quality, visibility impairment, and eutrophication (EEA, 2012).

Quantifying flare emission has been very challenging. There is still high uncertainty in the measurement of flare emissions and combustion efficiencies because they are not measured directly from actual industrial flares. Hence, emission factors have been widely used in most studies to quantify emissions from hydrocarbon combustion. However, emission factors are not available for some emissions from flaring operations. The EPA for example, has no emission factor for flares and enclosed combustors for NO_x, CO, PM, SO_2 and some GHG (EPA, 2013). An attempt is made here to predict the quantity of chemical species from the flaring of associated natural gas using the mass balance concept with varying air and combustion efficiencies.

The quantity of these emissions generated from flaring is dependent on the combustion efficiency. The combustion efficiency generally expressed as a percentage is essentially the amount of Hydrocarbon (HC) converted to CO_2. It is the ratio between the mass of carbon in the form of carbon dioxide which is produced by the flare and the mass of carbon in the form of fuel entering the flare (Alberta Flare Research Project). In other words, the combustion efficiency of a flare as used here is a measure of how effective that flare is in converting all of the carbon in the fuel to CO_2. Properly operated flares achieve at least 98 percent combustion efficiency in the flare plume, meaning that hydrocarbon and CO emissions amount to less than 2% of species in the gas stream (EPA, 1995). Pohl et al. (1984), Pohl and Soelberg (1985) demonstrated that properly designed and operated industrial flares are highly efficient. Other studies indicated that flares have highly variable efficiencies, on the order of 62–99% (Strosher 2000; Ozumba and Okoro, 2000; Leahey et al., 2001). In their experiments Becker (1974), Straitz (1977, 1978) cited in Gogolek et al. (2010), observed a combustion efficiency of 75% during smoking conditions but 99% with steam assist to eliminate smoke. A flare operated within the envelope of stable operating conditions will exhibit high efficiency unless too much steam or air assist (excess air) is used. Excess air has implications on emissions, specifically related to the creation of NO_x. The availability of extra nitrogen found in the air and additional heat required to maintain combustion temperatures are favourable conditions for the formation of thermal NO (EPA, 2012). More so, greater amounts of excess air create lower amounts of CO but also cause more heat loss.

2. Methodology

Emission estimates from flaring gas in elevated flares are predicted here by generating mass balance equations for various flaring conditions. This model depends largely on the number that precedes the formula for chemical species involved in the chemical reactions and is termed the stoichiometric coefficient. Mass balance in combustion analysis is central to determining flare combustion efficiency (Prateep et al., 2012; Johnson, 2008) and hence, flares emissions. Sonibare and Akeredolu (2004) investigated seven possible reactions (conditions) for flaring of natural gas using mass balance equations. Six of these were conditions that favour incomplete combustion. The general equation for complete combustion of pure alkanes (hydrocarbon) which are known to be the major constituent of natural gas is given by:

$$C_xH_y + \left(x+\frac{y}{z}\right)(O_2+3.76N_2) \rightarrow xCO_2 + \frac{y}{z}H_2O + 3.76\left(x+\frac{y}{z}\right) \quad (1)$$

For natural gas, very little systematic information is available concerning its chemical composition. Based on the chemical composition (Table 1), Eq. (2) can be written for the complete combustion of sweet natural gas.

$$[C_xH_y + aCO_2 + jN_2] + \left(x+\frac{y}{z}\right)(O_2+3.76N_2) \rightarrow xCO_2 + \frac{y}{z}H_2O + 3.76\left(x+\frac{y}{z}\right)N_2 + aCO_2 + jN_2 \quad (2)$$

where C_xH_y represent the known composition of total hydrocarbon (THC) of the flared gas. 'z' is equal to 4 for complete combustion, while 'a' and 'j' are the stoichiometric coefficients of the N_2 and CO_2 in the flared gas stream as shown in Table 1. Flaring in reality is rarely successful in the achievement of complete combustion (Leahey et al., 2001). Kostiuk et al. (2004) considered this by showing overall stoichiometry in estimating combustion efficiency as seen from a point downstream of the flare in Eq. (3). Hence, flaring is considered as an incomplete combustion process.

$$[C_xH_y + aCO_2] + b(O_2 + 3.76N_2 + vCO_2) + e(O_2 + 3.76N_2 + vCO_2) \rightarrow [fCO_2 + gH_2O + hCO + iC_{xx}H_{yy} + 3.76bN_2 + aCO_2 + bvCO_2] + [eCO_2 + 3.76N_2 + vCO_2] \quad (3)$$

where, 'b' and 'e' are stoichiometric coefficients for air in combustion and for air entrained into the plume without combustion, respectively. Considering the chemical composition (Table 1) and the following assumptions, Eq. (3) can be re-written for sweet natural gas (no presence of sulphur):

i. 'i' = 0, (no unburned hydrocarbon),
ii. 'v' is very small in the composition of air when compared to nitrogen and oxygen,
iii. 'e' = 0 (No ambient air entrained into the plume without combustion).

$$[C_xH_y + aCO_2 + jN_2] + b(O_2 + 3.76N_2) \rightarrow [fCO_2 + gH_2O + hCO + jN_2 + aCO_2] + 3.76bN_2 \quad (4)$$

The distribution of chemical specie on the product side of Eq. (4) is also a function of the molar fraction between the fully oxidized carbon and the partial oxidized carbon (Kostiuk et al., 2004). After algebraic manipulation and equation balancing, Eq. (4) can be re-written as:

$$[C_xH_y + aCO_2 + jN_2] + b(O_2 + 3.76N_2) \rightarrow \left[\alpha xCO_2 + \alpha\frac{y}{z}H_2O + (1-\alpha)xCO + jN_2 + aCO_2\right] + 3.76bN_2 \quad (5)$$

From Eqs. 1, 4, and 5, $b = \left(x+\frac{y}{z}\right)$, $f = \alpha x$, $g = \alpha\frac{y}{z}$, $(h = 1-\alpha)x$ and α is the molar fraction between oxidized