Environmental Pollution 216 (2016) 182–197

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Review

Gas flaring and resultant air pollution: A review focusing on black carbon☆

Olusegun G. Fawole [a, c], X.-M. Cai [a], A.R. MacKenzie [a, b, *]

[a] School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK
[b] Birmingham Institute of Forest Research, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK
[c] Environmental Research Laboratory, Department of Physics, Obafemi Awolowo University, Ile-Ife, 220005, Nigeria

ARTICLE INFO

Article history:
Received 23 February 2016
Received in revised form
24 May 2016
Accepted 26 May 2016

Keywords:
Gas flaring
Oil and gas
Black carbon
Incomplete combustion
Hydrocarbon
Emission factors

ABSTRACT

Gas flaring is a prominent source of VOCs, CO, CO_2, SO_2, PAH, NO_X and soot (black carbon), all of which are important pollutants which interact, directly and indirectly, in the Earth's climatic processes. Globally, over 130 billion cubic metres of gas are flared annually. We review the contribution of gas flaring to air pollution on local, regional and global scales, with special emphasis on black carbon (BC, "soot"). The temporal and spatial characteristics of gas flaring distinguishes it from mobile combustion sources (transport), while the open-flame nature of gas flaring distinguishes it from industrial point-sources; the high temperature, flame control, and spatial compactness distinguishes gas flaring from both biomass burning and domestic fuel-use. All of these distinguishing factors influence the quantity and characteristics of BC production from gas flaring, so that it is important to consider this source separately in emissions inventories and environmental field studies. Estimate of the yield of pollutants from gas flaring have, to date, paid little or no attention to the emission of BC with the assumption often being made that flaring produces a smokeless flame. In gas flares, soot yield is known to depend on a number of factors, and there is a need to develop emission estimates and modelling frameworks that take these factors into consideration. Hence, emission inventories, especially of the soot yield from gas flaring should give adequate consideration to the variation of fuel gas composition, and to combustion characteristics, which are strong determinants of the nature and quantity of pollutants emitted. The buoyant nature of gas flaring plume, often at temperatures in the range of 2000 K, coupled with the height of the stack enables some of the pollutants to escape further into the free troposphere aiding their long-range transport, which is often not well-captured by model studies.

1. Introduction

1.1. Motivation

Humans need energy to drive their technology and hence, make life pleasurable and worth living. Different forms of energy are in use and new ones are developed in order to meet the increasing needs of society (MacKay, 2008). This quest for dependable, affordable and environmentally benign energy sources has occurred throughout human history; for the last century or so, crude oil has been the focus of world energy. In 2011, crude oil was estimated to provide 52.8% of the world's energy (13113 Mtoe); with oil and natural gas accounting for 31.5% and 21.3% respectively (IEA, 2013).

Human reliance on oil and gas as an energy source is not without its attendant impact on the environment. During production, detrimental impacts on the environment (air, water and soil) include: oil spills and leakages; venting; sludge disposal; and flaring (Almanza et al., 2012; Osuji and Adesiyan, 2005; Osuji and Onojake, 2004; Sonibare et al., 2010). The post-production impact of oil and gas on the environment is also a major source of concern, but is not the subject of this review.

Gas flaring is often a routine daily activity in oil fields around the world, particularly in oil-rich regions of the world where the infrastructure to capture, store and utilise the gas produced is not available. Flaring is most often associated with Nigeria and the Russian Arctic, but it does still occur in more developed economies:

☆ This paper has been recommended for acceptance by Dr. Hageman Kimberly Jill.

* Corresponding author.
E-mail address: a.r.mackenzie@bham.ac.uk (A.R. MacKenzie).

http://dx.doi.org/10.1016/j.envpol.2016.05.075
0269-7491/

Variables used and their meanings

u_e	exit velocity of the flue gas (m s^{-1})
s	the air-fuel ratio
ρ_e, ρ_∞	the fuel gas and ambient densities respectively (kg m^{-3})
g	acceleration due to gravity (m s^{-2})
ΔT_f	mean peak flame temperature rise, K (taken as the difference between the adiabatic flame temperature and the ambient temperature)
d_e	burner diameter (m)
ν_o	kinematic viscosity of the gas-air mixture (m^2 s^{-1})
L	characteristic flame length (m)
$\dot{m}_o$	mass flux of the flue gas at the burner exit (kgm^{-2} s^{-1})
f_s	stoichiometric mixture fraction
ϕ	equivalence ratio
T_∞	ambient temperature

the North Dakota Bakken shale region, for instance (see, e.g., http://www.eia.gov/todayinenergy/detail.cfm?id=23752, last accessed on 29 January 2016). Despite several calls by international bodies such as the World Bank's Global Gas Flaring Reduction (GGFR) initiative, the volume of gas flared globally appears to have plateaued at around 130 billion cubic metres (bcm) since 2008, or may even have increased (see section 1.4, below). According to GGFR (2013), there was an increase of 2 bcm in the volume of gas flared in 2011 compared to the previous year. The latest in this series of initiatives by the World Bank - Zero Routine Flaring by 2030 - was launched by the Secretary-General of the United Nations, Ban Ki-Moon and World Bank's President, Jim Yong Kim, in May 2015 (see http://www.worldbank.org/en/programs/zero-routine-flaring-by-2030, last accessed on January 29, 2016).

Gas flaring, a prominent source of black carbon (BC) and other pollutants, has been ignored or underestimated in emission inventories and models, as a result of which models are struggling to predict measurements of BC in regions of intense gas flaring. The intensity of gas flaring and specifics of atmospheric transport can combine to enhance the role of gas flaring emissions over very large areas (e.g., the Arctic) (Stohl et al., 2013). Presently, treatment of emissions from gas flaring is rather rudimentary in most global emission inventories. As at 2015, to the best of our knowledge, only two global pollutants inventories explicitly accounted for emissions from gas flaring (see section 4.5).

Gas flaring is classified as a miscellaneous BC-rich source, a group which includes aviation and shipping which together contribute about 9% to global BC emission (Bond et al., 2013). Gas flaring is a very different type of combustion compared to other BC sources in this category; gas flaring is characterised by either fuel-regulated or oxidant-regulated open-fire (see below) resulting in flames that can be 8–10 m in length, with flame temperature as high as 2000 K. Gas flaring is a year-round activity in most of the intensive flaring regions of the world, and so differs from transport sources in being stationary and differs from other stationary sources (e.g. cooking and biomass burning) by being relatively constant in time. The GAINS (Greenhouse gas Air pollution INteractions and Synergies) model estimated that gas flaring contributes about 4% of total anthropogenic BC emissions, majority of which are from the leading gas-flaring nations; Russia, Nigeria, and countries in the Middle East (Bond et al., 2013; Stohl et al., 2013). Gas flaring is estimated to contribute 260 Gg to global BC estimates annually (Bond et al., 2013), while in Russia, it is estimated to have the largest contribution of 36.2% to anthropogenic BC emission (Huang et al., 2015). From a 3-year model simulation, more than 40% of annual mean BC near the surface in the Arctic is estimated to be contribution from gas flaring (Stohl et al., 2013).

Considering the small number of nations that still flare gas, a contribution of 4% to global BC represents a significant skew in the global apportionment of BC emissions. On a regional scale, the contribution of this 'overlooked' source of ambient aerosol loading is likely to be significant.

1.2. Review summary

For this review, we have collated previous studies (1984–2015) on gas flaring and its contributions to ambient aerosol loadings. This review is the first to cover virtually every aspects of gas flaring (process, trends, chemistry, flame dynamics and environmental impact). The review starts with a brief assessment of the level and distribution of oil and gas reserves around continents of the world. Compositional variation of the natural gas flared and their thermodynamic properties are discussed because they are likely to have significant impact on pollutant emission rates and overall amount. Next, we provide a discussion of the temporal and geographical trends in gas flaring, including brief comments about how weather conditions in regions where gas flaring is common will impact near-field dispersion and long-range transport. This is followed by a broad discussion of the gas flaring process itself; highlighting how engineering and technology decisions impact on the emission of air pollutants. Finally, several techniques used to estimate emissions from gas flaring are discussed. Throughout this review, special attention is paid to soot (i.e. carbonaceous aerosol predominantly composed of BC) emission from gas flaring because of the now known contribution of BC to global warming and the apparent neglect of the contribution of gas flaring to ambient air aerosol loadings in inventories and global models.

1.3. Global oil and gas reserves

World-proven natural gas and oil reserves at the end of 2012 stood at 187.3 and 1668.9 trillion cubic metres (tcm) respectively, sufficient to meet 55.7 years of global production (BP, 2013). The distribution of these reserves among regions of the world is shown in Fig. 1(a) and (b). The natural gas collected during the exploration of crude oil from the Earth's crust can be a very good source of fuel; transported in pipes for industrial or domestic use and also recycled back into the processing operation (Davoudi et al., 2013; Elvidge et al., 2009).

In developing countries and oil-rich regions where the technology, infrastructure, and market structure to put all of the natural gas to meaningful use are not available or inadequate, the excess natural gas then becomes a waste stream and is flared or vented. Gas flaring has been termed 'gross waste' by the World Bank's initiative against gas flaring (Global gas flaring reduction: GGFR), because flaring represents direct injection of fossil carbon into the atmosphere without capture and utilization of the heat produced by combustion.

1.4. Temporal and geographical trends in gas flaring

The all-time peak of volume of gas flared, 172 bcm, was in 2003 (Elvidge et al., 2009) although see estimates for 2012, below. Fig. 2(a) shows the quantity of natural gas produced by the top 10 oil producing nations of the world between 2000 and 2011, and for comparison, Fig. 2(b) shows the estimated quantity of gas flared by these major oil producing nations during the same period of time.