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Multi-objective optimization methodology to size cogeneration systems for managing flares from uncertain sources during abnormal process operations

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ABSTRACT

Flaring is common practice in industries to reduce the risk during abnormal situations, to maintain the product quality or to operate safely during process start up and shut down. Due to its large negative impacts on the environment and society, various protocol and steps, i.e., Kyoto protocol, the United Nations Environment Programme, have been created for future mitigation. There is significant amount of heating value lost during flaring events. A cogeneration (COGEN) system can use waste flare streams as fuel to generate heat and power within a process. The objective of this work is to develop an optimization framework for sizing a COGEN unit to manage flares from uncertain sources by minimizing the overall cost and emissions of greenhouse gases. Multi-objective trade-offs between the economic, environmental, and energetic aspects are presented through Pareto fronts for a base case ethylene plant using a stochastic optimization technique based on genetic algorithm.

1. Introduction

Flaring is a very common practice across all industrial plants. Industries usually flare to reduce the risk during abnormal situations, to maintain the product quality or to operate safely during process start up and shut down. Industrial flaring is a contentious economic, environmental and social issue because it does not only waste potentially valuable source of energy, it also adds significant carbon emissions and other toxic materials to the atmosphere that have been linked to cause cancers, asthma, chronic bronchitis, blood disorders, and other diseases in human health (Davoudi et al., 2013; Nwankwo and Ogagarue, 2011). Emissions from industrial flares contribute to global warming. The implications of global warming have been linked to the melting of ice and the rising of sea level, which can lead to flooding and tsunamis across the globe (Anomohanran, 2012; Azam and Farooq, 2005; Edino et al., 2010; Hassan and Kouhy, 2013; Joseph et al., 2011; Nordell, 2003; Yuqin et al., 2010).

Therefore, industrial flaring and its effect on the environment, ecosystem and society have gained the attention of researchers, environmentalists and policy makers. Numerous protocol, international agreement and steps such as the Kyoto protocol, the United Nations Environment Programme (UNEP), World Bank Global Gas Flaring Reduction (GGFR) Programme have been initiated to mitigate the impact of industrial flaring. This is essential to avoid dangerous anthropogenic interference with the climate system.

Many industrial countries around the world such as United States (US), France, and Saudi Arabia have attempted different alternatives to reduce the amount of gas flared in their country (Anomohanran, 2011, 2012; Jegannathan et al., 2011; Sharma et al., 2011). The US was able to reduce their emission level by 5.8% between 2008 and 2009 (Anomohanran, 2012; EIA, 2011). Some governments and legislation authorities have tightened their considerable limit. The State of Qatar has changed the acid gas flaring limit from 1% to 0.06% (Homssi et al., 2012). In an attempt to stop the flaring of associated gas, the Nigerian government established the Nigeria Liquefied Natural Gas plant to prevent the release of millions of tons of CO_2 into the atmosphere. Oil companies operating in Nigeria have established several alternatives to reduce gas flaring, i.e., Shell Petroleum Development Company of Nigeria (SPDC) installed equipment to capture gas from its facilities. Between 2000 and 2010, SPDC claimed that their flaring quantity dropped by half (Anomohanran, 2012; SPDC, 2011). France is an example where the introduction of nuclear power was able to reduce the emission drastically. Although, governments and companies have had success in reducing flare gas with

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Nomenclature

a_e	electrical power price ($/kWh)
a_f	unit fuel cost for the fuel f ($/MMBtu)
A_s	correlation parameter
B_s	correlation parameter
C_{Boiler}	capital cost of boiler ($)
C_{Fuel}	fuel cost ($)
C_{tax}	tax for CO_2 emissions ($/ton)
$C_{Turbine}$	capital cost of turbine ($)
e_{jp}	regulatory limit on pollutant j flared without penalty at flare in mode p
e_{ijkp}	amount of pollutant j that sink k would emit in mode p for 1 MMscf of fuel gas flared
GHG	green house gas
F_P	flexibility factor for the increase in pressure (Kamrava et al., 2015)
h	enthalpy (Btu/lb)
h_f	latent heat (Btu/lb)
H_Y	annual operation time (h/year)
k_f	factor used to annualized the capital costs (years^{-1})
LHV	lower heating value (Btu/lb)
N_P	factor to account for the operational pressure
N_T	factor for the superheat temperature
P_e	profit obtained for the electric power produced ($/kWh)
P_t	turbine shaft power output (Btu/h)
Q_b	heat required in the boiler (Btu/hr)
Q_f	amount of heat transferred from the combustion of fuel f to the steam at the boiler (Btu/h)
TAC	total annualized cost
T_{sat}	saturation temperature (°F)
s	entropy (Btu/lb °F)
Greek letters	
η_f	efficiency in the boiler for the fuel f
η_g	efficiency for the generator

significant investments, global gas flaring has remained largely stable over the past fifteen years in the range of 140–170 billion cubic meters (BCM) which is equivalent of 300 million tons CO_2 emissions (Davoudi et al., 2013). Therefore, much attention is still needed today to mitigate and manage industrial flares. Many researchers and companies are working simultaneously to find solutions for flare reduction. Recent articles and reports show different approaches have been suggested for effective flare reduction and utilization such as: utilization of renewable and alternative energy, process efficiency improvement, modernization and conversion of old techniques, waste streams recovery, combining heat and power through process integration, and innovative design solutions for flare gas utilization (Anomohanran, 2012; Jegannathan et al., 2011; Kamrava et al., 2015; Mohammed et al., 2014; Sharma et al., 2011). The concept of providing credits for carbon-reduction along with viable flare reduction solution can be the added incentive that push industries for adopting enhanced flare management, recovery and utilization strategies (He et al., 2012).

1.1. COGEN

Combined generation of different kinds of energy, for example heat and power, has become a mainstream practice in different industries due to high economic and energy-saving potentials (Foo, 2009; Kemp, 2009; Majozi, 2009; Noureldin, 2012; Rossiter, 2010; Smith, 2005). Cogeneration (COGEN) system mainly comprise of a boiler and a turbine where dual industrial process requirement of power and heating can be satisfied using a single fuel (Deneux et al., 2013; El-Halwagi, 2006, 2012; Kamrava et al., 2015). Boiler produces steam that is used to operate a turbine to produce shaft work for power generation. In gas processing facilities, flare streams mostly contain combustible hydrocarbon with significant heating values. Such streams can be valuable fuel sources, which can be used in boilers for steam generation. Hence, the use of a cogeneration system is a potential approach for reusing waste flare streams. The generation of heat and power from waste sources provides an attractive service of managing flare during process upsets. Ultimately, it will conserve fuel feed to COGEN and thereby reduce the amount of GHG emissions.

1.2. COGEN sizing

The size of the boiler in COGEN varies with heating utility demand and the size of the turbine varies with the amount of power generation. Therefore, the size of the cogeneration unit is defined in terms of amount of generated heat and power. The capital cost can be introduces as a function of other operation variables or as integers of a set of possible selections with their operation capacities. The effectiveness of COGEN systems as a flare mitigation technique is highly dependent on identifying its optimal size, which is determined by simultaneously assessing the economic performance, energy savings and environmental benefits (Al-Azri et al., 2009; Bamufleh et al., 2013; Gamou et al., 2002; Kavvadias and Maroulis, 2010). If the capacities of the prime movers are underestimated, the effect of introducing cogeneration units becomes relatively small, and if they are overestimated, the feasibilities decrease (Beihong and Weiding, 2006). Moreover, flaring during process upsets or abnormal situations in industry is an unpredictable incident. Therefore, a robust optimization methodology is needed for sizing the COGEN unit for uncertain process upsets.

1.3. CO_2 tax and credit

It is very important to account for the carbon tax saving while designing or planning for a COGEN unit for flare management. Actually, the main contribution of utilizing a COGEN unit will be to reduce the overall carbon emission while maintaining the heat and power requirements. The recycled flare streams to COGEN unit will compensate the CO_2 emissions of the fresh fuel feed. It will also reduce the cost of the fresh fuel feed for the cogeneration unit.

There are mainly two types of GHG emission tax systems. First, Carbon Tax system, where tax is being paid by the fuel suppliers at a rate that reflects the carbon content of distributed fuel. In other words, cleaner the fuel lowers the tax fees. On the other hand, cap and trade system (CAT), where tax is being managed by a regulatory authority (El-Halwagi, 2012). A plant might have regulatory limits on emissions of certain pollutants (e.g., CO_2) from all sinks. Those permits are valid for certain fixed time period recognized by the regulator. Representative who exceed their emissions permits have to pay extra tax fees. On the contrary, representatives who succeed in reducing their emissions are allowed to sell their surplus permit to another company who is in need for it. In this work, the optimization formulation was based on cap and trade system (CAT).

1.4. Global optimization

It is evident that the design of such economical & eco-friendly COGEN unit is not straightforward due to the conflicting objectives. Usually, a single-objective function, which is a weighted combination of several objectives, is not suitable for this kind of optimal sizing. It is often difficult to interrelate several