Iranian Journal of Chemical Engineering
Vol. 11, No. 3 (Summer 2014), IAChE

Effect of Various Parameters on Emission Factors of Gas Flares

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Abstract

The purpose of this study is development of some parametric emission factors for gas flares using pilot-scale flare and investigation of the effect and interaction of important parameters on the emission factors. The considered parameters were flame Reynolds number, superheat steam-air flow rate and wind speed. Every variable was considered in four levels and the experiments were carried out two times. The results of 128 experiments showed that the average emission factors of CO_2, CO and NO_x pollutants are 127.183, 0.731 and 0.074 lb/MMBtu (pound per Million British thermal unit), respectively. In addition, variance analysis of variables showed that the CO_2 and CO emission factors are significantly influenced by wind flow and NO_x emission factor is influenced by superheat steam-air flow rate.

Keywords: *Gas Flares, Emission Factors, CO_2, CO, NO_x*

1. Introduction

Flaring is a high-temperature oxidation process used to burn combustible components, mostly hydrocarbons, of waste gases from industrial operations. Natural gas, propane, ethylene, propylene, butadiene and butane constitute over 95 percent of the waste gases flared [1]. Emission of gases from flares into the air significantly affects the environment ecologically and economically. Since in gas flares the flame is on top of the flare and also because of their high altitude conventional emission measurement techniques are not applicable for direct determination of outlet contaminants. Therefore, emission factor method is used to estimate the amount of pollutants emitted from gas flares [2].

Emission factors are representative values that attempt to relate the quantity of a pollutant released to the ambient air with an activity associated with the release of that pollutant [3]. Unfortunately, there is a relatively high uncertainty in implementation of emission factors reported in literature for flares [4-9]. Therefore, it is necessary to revise the emission factor gas flares, especially taking combustion influencing

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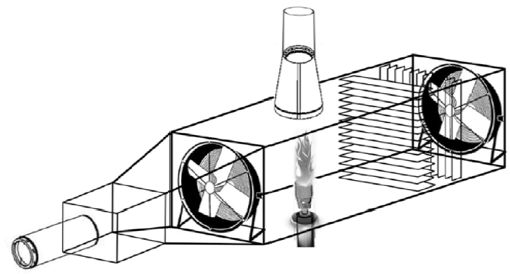
parameters into consideration.

In this study, the emission factors for a gas flare in pilot scale were developed by considering the influence of some practical parameters including Reynolds number, superheat steam-air flow rate and wind speed. To consider operating conditions as close as possible to the actual conditions, Tabriz Petrochemical flare data was used in pilot flare construction. The pollutants considered in this study are CO, NO_x and CO_2. It is expected that the emission factors obtained in this study be more precise in comparison to the published emission factors for gas flares.

2. Methods

2-1. The set up gas flare description

Fig. 1 shows the Schematic of the experimental setup of gas flare used in this study. Taking dimensional analysis and operating condition of Tabriz city Petrochemical flare data sheet as an example, we intended to use a ⅛" nozzle with a 4 inch nozzle head to ensure the suitable formation of flame front at nozzle exit [5]. Superheat steam and fresh air were injected through nine nozzles with a 0.5 mm diameter. As depicted in Fig. 1 (b), these nozzles were placed in a circular pattern with a 1.5 cm diameter and 45 degre einjectionangle. An ignition electrode was embedded near the nozzle exit to prevent flame blackout while injecting steam. K type thermocouple indicator (T4WM series, Autonics USA, Inc.) was applied to measure flame temperature. The mixing chamber for complete mix of gases has a dimension of 60 cm in length and 4 cm in inner diameter. A peristaltic pump was used to supply water to evaporator. In order to study the effect of wind on flame stability and the amount of pollutants generated, the wind was simulated by means of a wind tunnel. The implemented wind tunnel has a rectangular cross section of dimensions 55cm × 45cm and length of 115cm. Two fans with the variable speed were planted on the sides of the tunnel. The one with higher speed (2000 rpm) was located at outlet of the tunnel and the other one with slower speed (1440 rpm) was located at the inlet of the tunnel. These type of fans are necessary to prevent the excessive compression of air around the flame and create the vortexes in the corners. As depicted in Fig. 1, four Flat blades were placed in front of the flame in order to ensure the uniformity of flow over the flame.



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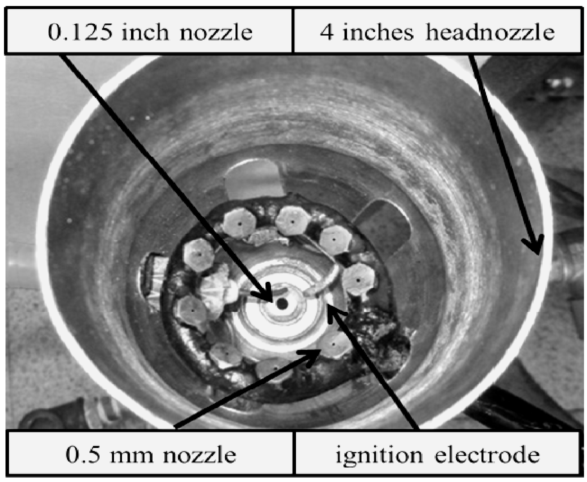


(b)

Figure 1. (a) Schematic of the experimental setup, (b) picture of nozzles, nozzle head and ignition electrode.

A mixture of Methane, ethane, propane, butane, ethylene, propylene and nitrogen was used as a fuel gas. This combination was chosen based on analysis of supplied gases to Tabriz petrochemical flare as an average of flare gas composition in three-month period. Chemical analysis of flared gas is presented in Table 1. An IR-Analyzer device (Vario plus Industrial, MRU instruments, Inc.) was used to measure pollutants concentrations. Simulated wind velocity was measured and recorded by a digital anemometer.

2-2. Experimental design method

In this study, we used experiment design prior to proceeding with experiments in order to investigate the effect of each parameter on the amount of pollutant emission. Design Expert software version 7.0.0 (Stat-Ease, Inc.) was used for the design and analysis of experiments. By considering general full factorial design, it is concluded that 2×43 tests are required. These experiments were carried out on a complete random order without blocking.

Each experiment was replicated once more in order to verify the precision of the results and to calculate error sum of squares (SS error). To study the effect of input variables on CO_2, NO_x and CO concentration, statistical F-Test and P-value procedure were employed. As a result, parameter with P-value less than 0.05 had a significant influence on the out put results. The closer the P-value to zero, the more effective the related parameter is. If there are two input variables with the same P-value, the one with larger F-value has more effect on the response [10]. The effective parameters in the present study are Reynolds number, wind speed and superheat steam-air (at 140^{o}C) flow rate [2]. Reynolds number is used herein because of analysis of turbulency in flame zone. In high flame speed, according to high Reynolds number, the mixing rate of fuel gas and air is better. Thus, combustion efficiency increases because of turbulency. Similarly, the steam injection to flame, in addition to increasing mixing rate, can effectively reduce the flame temperature, which leads to NO_x reduction. Four levels were specified for each input parameter in DX7 software. The considered parameters and their levels are shown in Table 2.

Table 1. The analysis of fuel gas used in experiments.

Gases	Molecular Formula	Mole fraction (%)	Mass fraction	Molecular weight (g/mol)
Methane	CH_4	20	0.1011	16.043
Ethane	C_2H_6	5	0.0473	30.069
Propane	C_3H_8	5	0.0694	44.096
Butane	C_4H_{10}	15	0.2745	58.123
Ethylene	C_2H_4	15	0.1325	28.054
Propylene	C_3H_6	5	0.0662	42.080
Nitrogen	N_2	35	0.3087	28.013

Table 2. The level and ranges of considered factors in experiments

Parameters	Level 1	Level 2	Level 3	Level 4
Reynolds number	2000	3000	4000	5000
Wind speed (m/s)	0.0	0.3	0.6	0.9
Superheat steam-air (cc/min)	1000	1400	1800	2200

EPA method 19 was used to calculate emission factors of pollutants based on lb/MMBtu unit (pound per million British thermal unit) according to Equation 2 [11]:

$$EF = \frac{C_{ppb} \times F \times Mw}{(V \times 10^9)} \times T_{Correction} \times Oxygen_{Correction} \quad (1)$$

Where *EF* is Emission factor in lb/MMBtu of pollutant. C_{ppb} is pollutant concentration in ppb (part per billion based on dry volume). *Mw* is molecular weight of the CO_2 (lb/lb-mole). *V* is volume occupied by 1 mole of ideal gas at standard temperature and pressure (385.5 ft^3/lb-mole @ 68 $^{\circ}$F and 1 atm) and *F* is the factor defined as the ratio of gas volume of the products of combustion to the heat content of the fuel. F includes all components of combustion excluding water. In this study, F was provided from EPA reference method 19 as an average for natural gas (8710 dscf/MMBtu- dry standard cubic feet per million Btu) determined at standard conditions (20^{o}C and 1 atm). To correct F Factor according to temperature (to 68^{o}F) and oxygen correction (to 0% O_2) the following equations were used.

$$T_{Correction} = \frac{528\ ^{o}R}{(460\ ^{o} + T\ ^{o}R)} \quad (2)$$

$$Oxygen_{Correction} = \left(\frac{20.9}{20.9 - \%O_2}\right) \quad (3)$$

Where T ^{o}R Rankine degree is reference temperature of F factor and $\%O_2$ is percent of oxygen in exhaust by volume. The error of averaged emission factor was calculated using the following formula:

$$E = t \times \frac{S}{\sqrt{n}} \quad (4)$$

In equation 4, E is the error, n number of data, S standard deviation and t is t-value assuming 95% confidence level [12].

3. Results and discussion

3-1. Averaged Emission factors

As seen in Table 3 the average value of CO_2, CO and NO_x emission factors are obtained 127.183, 0.731 and 0.074 lb/MMBtu respectively. These values were calculated by averaging the results of 128 experiments. Flame Reynolds numbers were in the range of 1000-5000, superheated air-steam volume flow rates were in range of 1000-2200 cc/min with air to steam volume ratio of 1 to 4 (based on 140°C of temperature). Wind velocity varied from zero to 0.9 m/s and the flame temperature was measured in the range of 400-700°C.

Table 3. The average and ranges of the measured Emission factor values.

Pollutant	Averaged EF (lb/MMBtu)	n	DE (Degree of Freedom)	t-student (95%)	S	E
CO_2	127.183	128	127	1.98	17.3781	3.0517±
CO	0.731	128	127	1.98	0.5263	0.0945±
NO_X	0.074	128	127	1.98	0.0402	0.0072±

If measured emission factors are compared, for example, with reported emission factors by (Regional Association of oil and Natural Gas companies in Latin America and the Caribbean) ARPEL and united states Environmental Protection Agency (EPA) values it can be seen that there are differences between values [13-14] (Table 4). ARPEL and EPA offer higher or lower values for the emission factors respectively. So, it should be concluded that if the general emission factors used to calculate pollutant emissions values in gas flares, higher or lower than the actual values will be estimated.

Table 4. Comparison of emission factors with some published emission factors (lb/MMBtu).

	CO	NO_2	CO_2	Reference
EPA	0.37	0.068	117.65	[13]
ARPEL	1.3	0.098	Not Determined	[14]
(This Work)	0.73	0.074	127.18	

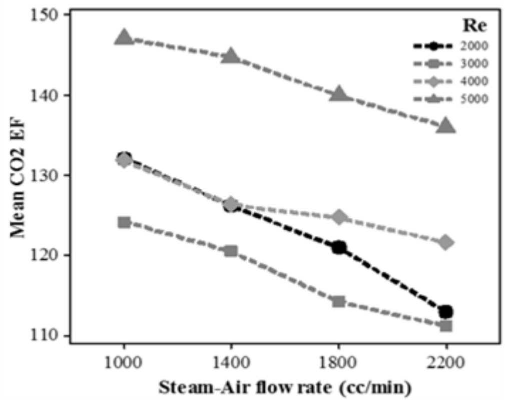
3-2. Statistical analysis of the data

We consider individual effects of each factor and their interactions on emission factors values using variance analysis. The result of variance analysis, P-values and F-value (ANOVA Table) of emission factors is shown in Table 5.

The ANOVA Table indicates that all considered parameters have individually influenced on the emission factors. Besides, there is some interaction between parameters. There are significant interactions between the Reynolds number (Factor A) and wind velocity (Factor C) on CO_2 emission factor. In order to interpret the results of experiments, a plot of the average responses (pollutants emission factors) at each test combination is illustrated in Fig. 2. a. and b. for CO_2. From these results, it is obvious that wind velocity has the greatest impact on CO_2 emission factor variation, while the superheated steam-air flow rate has the least effect. The conclusion is that flames imposed to wind have less efficiency than those burned in the absence of wind. This result is unexpected. Because, based on some researches, wind blowing can reduce the actual air to fuel ratio in comparison to stochiometric air to fuel ratio [15]. Under these conditions, combustion efficiencies can be quite low. Thus, it seems that the air concentration near the larger flare is considerably lower than that of smaller flames. The important fact obtained from the results is that in the pilot flare, when flame is imposed to wind flows, the air concentration increases near the flame zone. Wind velocity has the greatest effect on variation of CO emission factor too. CO emission increased with increasing wind velocity. It is an expected result, since an increase in wind speed can lead to incomplete combustion [15].

As another result, it can be seen that although there is not a significant influence on the emission factor of CO_2 at the low Reynolds number, in high Reynolds number (5000) because of better mixing of fuel with air, the CO_2 production increases. Thus, as described previously, the combustion efficiency can be increased with good mixing on flame zone.

Reynolds number variation has the least effect on CO emission factor in comparison with other parameters. However, unlike the CO_2, superheated steam-air flow rate has a significant influence on the CO emission factor. Results show that discharge superheated steam-air flow rate had the greatest impact on NO_x emission factor. Note that in the small flames, the flame temperature does not exceed 700°C. Therefore, the amount of NO_x production will not exceed a certain value. The more superheated steam-air is injected to the flame, the more the flame temperature and NO_x emission are reduced.



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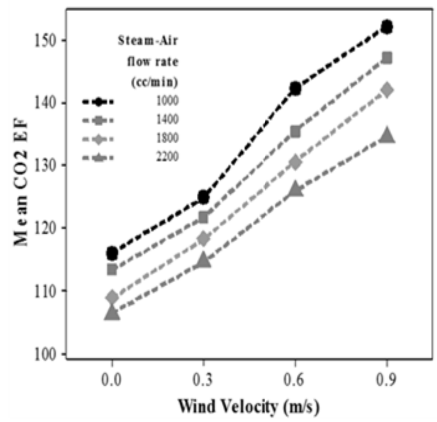

(b)

Figure 2. The effect of parameters on CO_2 Emission factor (lb/MMBtu) (a) the effect of Steam-Air flow rate (b) the effect of Wind Velocity.

Table 5. Pollutants Emission Factor F and P- values based on Design Expert ANOVA.

Pollutant		CO_2		CO		NO_x	
	DF	F- Value	P- Value	F- Value	P- Value	F- Value	P- Value
Model	36	61.88	< 0.0001	365.40	< 0.0001	25.63	< 0.0001
A- Reynolds Number	3	208.96	< 0.0001	33.26	< 0.0001	70.57	< 0.0001
B- Steam- Air Flow Rate	3	63.83	< 0.0001	196.17	< 0.0001	186.29	< 0.0001
C- Wind Velocity	3	404.05	< 0.0001	3957.23	< 0.0001	9.84	0.0001
AB	9	1.68	0.1418	1.43	0.2261	7.37	< 0.0001
AC	9	18.66	< 0.0001	39.24	< 0.0001	1.44	0.2195
BC	9	1.58	0.1712	25.38	< 0.0001	4.80	0.0007
R-Squared	0.9880			0.9872		0.9716	
Adj. R-Squared	0.9721			0.9802		0.9337	

4. Conclusions

Estimation parametric emission factors using direct measurements of pollutants could be the most accurate method for setting gas flares emission factors. In this work, in order to estimate emission factors as accurately as possible, variables including flame Reynolds, superheat steam-air flow rate and wind speed were considered based on pilot gas flare emission test. These variables strongly influence the efficiency of the combustion process in actual flares. The measurements of gaseous Emission factors of this work showed that there are differences between measured and published emission factors. Thus, according to the results of this investigation, neither of the general emission factors is fully applicable for estimation of pollutants in gas flares. This work showed that emission factors of gas flares strongly depend on both operating conditions and ambient characteristics. The statistical analysis of emission factors indicated that the CO_2 and CO emission factors are significantly influenced by wind flow and NO_x emission factor is influenced by superheat steam-air flow rate. These parameters can be important in the control of gas pollutants and in the design of flares with high combustion efficiency.

References

[1] Talebi, A., Fatehifar, E., Alizadeh, R. and Kahforoushan, D., "Estimation and evaluation of new CO, CO_2 and NOx emission factors for gas flares using pilot scale flare", Energy Sources, Part A Recovery, *Utilization, and Environmental Effects*., 36, 719 (2014).

[2] U.S. EPA, Flare Head Design and Gas Composition, Air and Energy Engineering Research Laboratory, Research Triangle Park, North Carolina, USA, (1985). [Available at: www.EPA.gov.

[3] Ramaswami, A., Milford, J. B., and Small, M. J., Integrated environmental modeling: pollutant transport and risk in the environment, John Wiley & Sons, New York, USA, p. 688 (2005).

[4] American Petroleum Institute (API), Compendium of Greenhouse Gas Emissions Estimation Methodologies for the Oil and Gas Industry, Texas, USA, (2004). [Available at: www.api.org/.../ 2009_GHG_COMPENDIUM]

[5] Pohl, J. H. and Soelberg, N. R., Evaluation of Efficiency of Industrial Flares: Flare Head Design and Gas Composition," EPA Report No., EPA/600/286/080 p. 140 (1986). [Available at: nepis.epa.gov]

[6] Kostiuk, L.W. and Thomas, G.P., Characterization of Gases and Liquids Flared at Battery Sites in the Western Canadian Sedimentary Basin, Technical Report, University of Alberta, Edmonton, Canada, p. 95 (2004).

[7] McDaniel, M. Flare efficiency study, US. Environmental Protection Agency report: EPA-600/2-83/052, Texas, USA, (1983). [Available at: www.EPA.gov.]

[8] Strosher, M. T., "Characterization of Emissions from Diffusion Flare Systems", *J. Air Waste Manag. Assoc*., 50 (10), 1723 (2000).

[9] Blackwood, T. R., "An evaluation of flare combustion efficiency using open-path Fourier Transform infrared technology", *J. Air Waste Manag. Assoc.,* 50 (10), 1714 (2000).

[10] Lazic, Z. R., Design of Experiments in Chemical Engineering: A Practical Guide, WILEY-VCH Co., Weinheim, Germany, p. 610 (2004).

[11] U.S. EPA, Quality assurance handbook for air pollution measurement systems, Vol. III., Stationary source-specific methods, Interim edition, EPA-600/R-94/038c,

Research Triangle Park, North Carolina, USA, (1994). [Available at: www.EPA.gov]

[12] Montgomery, D.C., Design and Analysis of Experiments, 4th Ed., Wiley, New York, USA, p. 752 (1997).

[13] Kahforoushan, D. and Fatehifar, E., "Development and evaluation of emission factors for gas turbines (multi-pollutant) in oil and gas processing plants", *Energy Sources, Part A Recovery, Utilization, and Environmental Effects*, 33 (4), 275 (2011).

[14] U.S. EPA, AP-42, Compilation of Air Pollutant Emission Factors, 5th ed., Vol. I, Research Triangle Park, North Carolina, USA, (2000). [Available at: www.EPA.gov]

[15] Leahey, D.M., Preston, K., and Strosher, M, "Theoretical and Observational Assessments of Flare Efficiencies", *J. Air Waste Manag. Assoc.*, 51 (12), 1610 (2001).