

Flare Gas Recovery of Olefin Unit: Flare Gas Flowrate Soft-Sensing

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ABSTRACT: In this paper the results of a study on reducing or recovering of the flare gases of the olefin unit of the Amirkabir petrochemical complex in southwest of Iran is reported. In particular, the focus of the paper is on the mass flowrate measurement of flare gases (mainly H₂ and CH₄) which is not an easy task in units without required devices installed. Since, generally, the flare gases are not the first priority in the unit operation, and the costs involved, usually these devices do not exist. Considering the characteristic of flare gases, the available portable measurement devices are unable to reliably measure the flare gas mass flowrate, and therefore, indirect or soft-sensing approach was used. Three indirect approaches were used to ensure the accuracy of the results. It was concluded that flare gas recovery unit is not needed; meanwhile, four scenarios were introduced to stop burning about 10000 kg/hr flare gas and techno-economical analysis were performed to rank them. The direct profit could be as much as ten million dollars annually, in addition to preventing of the discharge of a considerable amount of harmful burned gases to the atmosphere.

Keywords: energy, flare, recovery, environment, flowrate, soft-sensing

NOMENCLATURE

C_v	Valve Flow Coefficient
D	Pipe Diameter
d	Nominal Valve Diameter
F_k	Ratio of Specific Heat Factor
F_p	Piping Geometry Factor
f_f	Friction Factor
L_m	Pipeline Length
M	Molecular Weight
m_i	Mass flow of component i
m_T	Total mass flow
N₂	Conversion Coefficient
N₈	Conversion Coefficient
P₁	Inlet Pressure
P_b	Reference Pressure
T₁	Inlet Temperature
T_b	Reference Temperature
W	Mass Flow Rate
X	Ratio of Pressure Drop to Absolute Inlet

	Pressure
X_T	Pressure Drop Ratio Factor
Y	Expansion Factor
y_i	Molar fraction of component i
Z	Compressibility Factor
TCI	Total Capital Investment

1. INTRODUCTION

Petrochemical complexes are amongst the industries with a high demand for energy, usually in the form of fossil fuels. Olefin units are the heart of many petrochemical complexes and crack the liquid or gas feed to provide the feed to many down-stream units. They use a lot of energy to increase the temperature and crack the feed, and require a sophisticated flare system to

prevent possible dangers or explosions in case of any unexpected unit trip or shut down which necessitates the purging of all gases in the unit. Considering the huge amount of gases in the unit, the gas header to flare is usually very large, with a diameter about fifty inches. Also, usually there is a continuous altering amount of gas to flare for safety measures and because of unit mal-operation. The recovery of altering continuous flow (about 10000 kg/hr) was investigated in this work.

The emissions due to combustion of flare gases are harmful to environment, especially, when they carry acid gases. It is agreed by all experts in the process industry that the flaring should be minimized as much as possible to prevent the environment destruction. The goal in this project was to reduce or recover the flare gases as much as possible before they are being sent to olefin main flare for burning. This requires a techno-economical analysis of the flare system, and the feasibility study of flare gas recovery system in the unit.

One of the main tasks in this analysis is to measure the mass flow rate of the gases sent to flare as it is not a steady flow and changes, almost, continuously. Also, considering the safety rules, any instrumentation or device which may disturb the flow of gases could not be inserted in the gas header to flare. In addition, since the flow sent to flare is not important for operation, no measuring device is installed in the gas header, though the different scales of flow rate of gases make the required measurement not an easy task. The portable flow rate measuring devices for gases is not yet fully trustable, and in the gas headers with low pressure and large diameters it is hardly possible to produce reliable results.

Considering the above discussion, a soft-sensing approach is used in this work to obtain the gas flow rate to the olefin main flare of the Amirkabir petrochemical complex in southwest of Iran. Three approaches based on laboratory results of flare gas composition plus the hydrogen

flow rate readings in the control room, valve openings in seal drum and simulation of the flow between knock out drum and seal drum are implemented to ensure the reliability of the results.

2. REDUCING EMISSIONS FROM PLANT FLARES

There are two approaches to reduce emissions from plant flares [1]:

1. Improve unit operation to decrease produced gas sent to the flare
2. Flare gas recovery

2.1 Improve Unit Operation

The flaring is used to describe a naked (open) flame that is burning off excess gas which usually occurs at chemical plants. Generally, during routine operations the flare system burns smokelessly, quietly and largely unseen. When a process unit is shut down or during upset conditions, there can be higher flaring rates than base line levels. Poor control by plant staff or closing to plant life causes these problems.

In the Technical Exchange on Startup/Shutdown practices [11], petrochemical facilities shared case studies and examples of methods used to reduce flaring. Key findings on ways to reduce emissions include:

- ✎ Training of operators
- ✎ Improving the control parameters
- ✎ Better documentation of procedures highlighting environmental impacts
- ✎ Allowing additional time for start-up and shutdown

In fact, most of the operating problems could be solved using complete plant reorganization.

2.2 Flare Gas Recovery

There are many options to utilize vented/flared gas including purification and transport, gas re-injection, electricity generation, processing to LNG or CNG and conversion to other products [2].

A flare gas recovery unit (FGRU) takes excess gases from refinery operations, that would normally be burned in the flare, and compress it to a pressure, high enough, so it can be reused. FGRU provides the benefit of conservation of resources and reduction of emissions by recovering vent gases instead of flaring.

There are many alternatives for use of compressed gas. Choosing the best method depends on the related process, gas composition and flow rate. In this study, gas recovery of olefin main flare of Amirkabir petrochemical plant was investigated, nevertheless, this procedure can be extended to other flares.

Gas composition and flow rate are two main parameters for investigation of flare system. Generally, the gas chromatogram is used to determine flare gas composition. However, measurement of the flare gas flow rate is not straightforward and requires further investigation which shall be discussed in the followings.

3. FLARE GAS MASS FLOWRATE MEASUREMENT

There are many challenges in the measurement of the flare gas flow rate, including [3]:

- ✚ Large header pipe diameter
- ✚ High flow velocities over a wide range
- ✚ Low pressure
- ✚ Dirt, wax, CO₂, H₂S and condensate

Insertion turbine, thermal and averaging point tubes have been tested in flare flow rate metering applications. Each device has advantages and disadvantages for flare measurement. Tables 1 and 2 summarize metering characteristics of the flare gas flow meters [4].

As indicated in these tables, ultrasonic flow meter is a good choice for the flare gas flow measurement; while the other meters do not have all the necessary features to carry this measurement accurately.

Table 1: Specifications of Flow Meters

	Accuracy at High velocities	Accuracy at Low velocities	Accuracy at Large pipe diameter
Thermal mass	✗	✓	✗
Pressure Difference	✗	✗	✗
Insertion turbine	✗	✗	✗
Ultrasonic	✓	✓	✓

Table 2: Specifications of Flow Meters

	Sensitivity to excess component	Sensitivity to change gas composition	High Turndown
Thermal mass	✓	✓	✓
Pressure Difference	✓	–	✗
Insertion turbine	✓	–	✗
Ultrasonic	✗	✗	✓

There are two primary types of ultrasonic flow meters:

✚ In-line ultrasonic meters

The key focus of this study is to effectively reduce flared and vented gas volumes in the olefin unit. Accurate monitoring of flared and vented gas flow rate is an important part of the prioritization and management of the gases sent to the flare system. This requires the installation of metering devices such as in-line ultrasonic meters, consistent with the flare gas conditions, to continuously meter the total volume of gas sent to the flare.

Implicating obligatory rules and regulations for more extensive monitoring and reporting of flare emission, will force industries to think more seriously about installing these devices. As a minimum, operators should be obliged to report daily emissions.

🔧 Portable ultrasonic meters

Portable ultrasonic transit time flow meters, once restricted to liquids, have now been demonstrated on a variety of industrial gases. These applications range from air at atmospheric pressure (if the conduit is plastic) to pressurized gases such as steam, methane, or nasty gases typically pressurized to higher than 4 bar in steel pipe, and preferably greater than 10 bar [5], depending on pipe conditions, gas attenuation, Mach number, and gas molecular weight. Due to high range of flare applications and low pressures, the measurement of this parameter for this application is not reliable [4].

4. SOFT-SENSING METHOD

Considering the discussions in the previous section about the impossibility of application of direct measurement devices for the measurement of flare gas flow rate, an in-direct or soft-sensing approach is used in this work to obtain the gas flow rate using upstream or downstream information and required equations and calculations.

Bearing in mind the uncertainties in the soft-sensing measurements, and to ensure the accuracy of the results, three methods, rather than only one method, were implemented for the flare gas flow measurement as follow:

1. Flare gas molecular composition from laboratory tests plus the hydrogen mass flow rate from the control room on-line monitoring system.

2. Valve openings on the seal drum of the flare gas and steam, and valve specifications in the data sheet.

3. Simulation of the flow between knock out drum and seal drum using measured pressure and temperature values on two drums in the site, and gas composition from laboratory.

Brief discussions of three methods are presented here, detailed description can be found in reference [10]

4.1. Gas Composition Method

It is possible to determine total mass flow rate of a chemical composition by knowing mass fraction of components and mass flow rate of a particular component. Consider a multi-component system of n species; according to the equation (1) for gas mixture, total mass flow rate is calculated by equation (2) knowing mass flow of component i (m_i) [6].

$$\sum_{i=1}^n y_i = 1 \quad (1)$$

$$m_T = \sum_{i=1}^n m_i = \frac{m_i \sum y_i M_i}{y_i M_i} \quad (2)$$

The mass flow rate of H_2 is monitored on-line in the control room. Therefore, this method can be used to obtain mass flow rate of flare gases.

4.2. Valve Openings in the Seal Drum Method

The equation for the flow of a gas or vapour through a valve is as follows [7]:

$$W = C_V N_8 F_P P_1 Y \sqrt{\frac{XM}{T_1 z}} \quad (3)$$

The piping geometry factor (F_P) is defined as the ratio of the value C_V installed with reducers to the rated C_V of the valve installed without reducers. The equation (4) can be used to determine F_P [8]:

$$F_P = \left[1 + \frac{\sum K}{N_2} \left(\frac{C_V}{d^2} \right)^2 \right]^{-1/2} \quad (4)$$

The expansion factor (Y) accounts for the change in the fluid velocity as it pass from the valve inlet to the vena contract. It is calculated by equation (5) [7]:

$$Y = 1 - \frac{X}{3F_k X_T} \quad (5)$$

The flow rate through a valve is affected by the ratio of the specific heats (k) for the compressible fluid. The factor F_k accounts for this effect. The equation (6) is used to calculate F_k [7]:

$$F_k = \frac{k}{1.4} \quad (6)$$

The valve openings were read from valves indicators and in the control room.

4.3. Simulation of the Gas Flow from Knock-Out Drum to the Seal Drum

The steady-state, isothermal flow behaviour of gas in pipelines is defined by a general energy equation of the form [9]:

$$Q = 0.018 \left(\frac{T_b}{P_b} \right) \sqrt{\frac{1}{f_f}} \left[\frac{P_1^2 - P_2^2}{\gamma L_m T_{ave} Z_{ave}} \right]^{0.5} D^{2.5} \quad (7)$$

The Panhandle A equation uses the following expressions of Reynolds number and transmission factor:

$$\sqrt{\frac{1}{f_f}} = 6.872 (\text{Re})^{0.07305} \quad (8)$$

Substituting Eq (7) in the general energy equation (Eq (8)), the Panhandle A Equation becomes:

$$Q = 0.191 \left(\frac{T_b}{P_b} \right)^{1.0788} \left[\frac{P_1^2 - P_2^2}{\gamma^{0.853} L_m T_{ave} Z_{ave}} \right]^{0.5392} D^{2.6} \quad (9)$$

This equation was intended to reflect the flow of gas through smooth pipes. Home-developed software was used to simulate the gas flow through the pipe.

5. MEAUREMENTS

After choosing appropriate measurement methods, the required data for these methods should be measured.

Sample of the flare gas were collected three times per day, and the total number of eight samples were analyzed in the laboratory to obtain the gas composition. On the same time, the mass flow rate of H₂ was recorded from the control room computer system, using FI-30812.

In the valve opening method, flared gas valve opening (PV-73102A, PV-73102B), and steam valve opening HV-73105 were recorded from the control room computer system and on the valves indicators. The required data were measured six times per day, for nine days.

Finally, the pressure drop should be specified for the simulation of gas flow through the pipe. Hence, the gas seal pressure was recorded from PT-73102. The

pressure of the warm blow down (D-7131) and the knock-out drum (D-7132) were also recorded onsite using precise pressure metering devices with the accuracy of one kilopascal. Considering the low pressure drop, due to the low gas density and short distance between two drums, this precision is needed. Whereas the gas composition is also needed for the simulation, the required data were collected on the same schedule of the gas composition method.

6. RESULTS

The results of the calculations based on the data collected from plant are as follow.

6.1. Gas Composition

As the composition of the waste gases going to the flare is often varying; a mean mol percent for each component is considered in the gas composition. The Amirkabir flare gas molecular composition (minimum, maximum and mean mole percentage values), based on the laboratory results, is presented in table 3.

Table 3: Flare Gas Composition

Component	Mol % (min)	Mol % (max)	Mol % (mean)
H ₂	83.69994	86.42993	85.06494
CO	0.18	0.49	0.335
CO ₂	0.000013	0.000069	0.000041
CH ₄	11.73	13.98	12.855
C ₂ H ₆	0.02	0.44	0.23
C ₂ H ₄	0.06	0.81	0.435
C ₃ H ₈	0.01	0.07	0.04
C ₃ H ₆	0.03	0.28	0.155
N-C ₄	0.01	0.06	0.035
I-C ₄	0	0.03	0.015
Propadiene	0	0.01	0.005
C ₂ H ₂	0	0.01	0.005
1-Butene	0	0.02	0.01
I-Butene	0	0.11	0.055
1,3-Butadiene	0	0.07	0.035
C ₅ ⁺	0.04	0.15	0.095
N ₂	0.58	2.67	1.625
Total	100	100	100

6.2. Flare Gas Mass Flowrate

The results obtained by three soft-sensing methods for the flare gas mass flowrate are presented in figures one to three, respectively [10]. The daily average values of the flare gas mass flow rates obtained are presented, along with their mean, standard deviation and maximum error percentage with respect to the mean values.

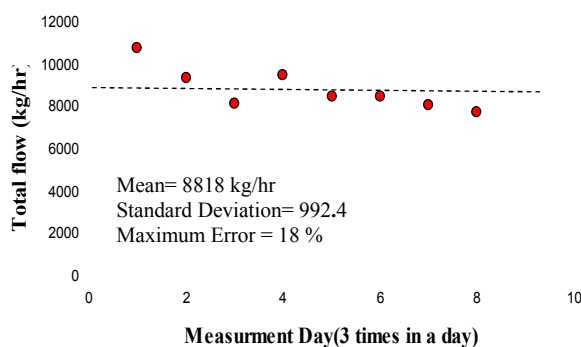


Figure 1: Flare gas mass flowrate from gas composition method

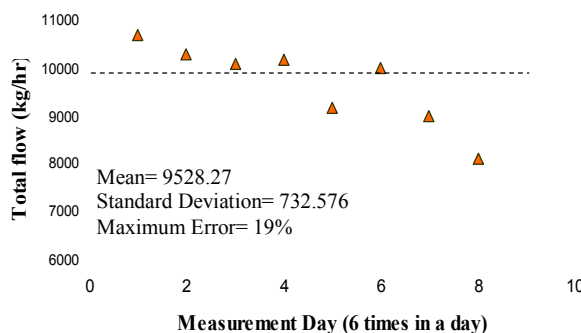


Figure 2: Flare gas mass flowrate from valve opening method

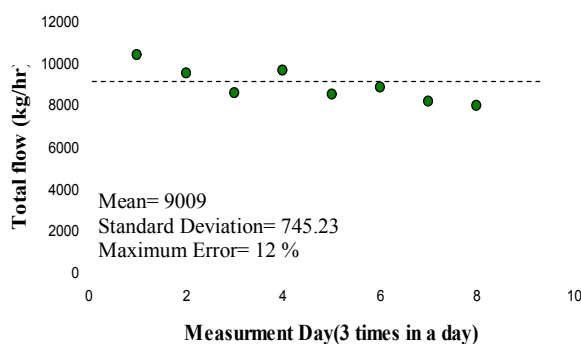


Figure 3: Flare gas mass flowrate from simulation method

As can be seen, the results are quite similar, which indicates that the soft-sensing approach used is successful in estimating the flare gas mass flow rate. [10].

The mean values of the flare gas mass flowrate from three proposed methods, along with their mean and maximum errors are listed in table 4. It is found that the range of flow rate is 8818 – 9528 kg/hr and the mean error is less than 9%.

Table 4: Mean flow rate and errors

Method	Mean flow (kg/hr)	Mean error (%)	Maximum error (%)
Gas composition	8818	8.7	18
Valve opening	9528	7.4	19
Simulation	9009	7.54	13

The flare gas mass flow rate of the Amirkabir olefin plant is estimated to be 9173 ± 355 kg/hr.

6.3. Techno-Economical Analysis

The Amirkabir flare gas mainly consists of hydrogen and methane (table 3). The disposal pressure of this gas in the unit is about 23 bars, therefore, the best approach is to stop sending it to the flare system and directly use it for other purposes. In other words, recovery should be accomplished at the disposal point, and the standard flare gas recovery unit is not needed in this case.

The proposed methods for the recovery of this flare gas are [10]:

- Sale of gas (86% by mole H_2)
If an adjacent plant buys this gas, it is a good solution with no capital investment.
- Separation of hydrogen/methane mixture
Flared gas is valued for its hydrogen content. Therefore, it could be beneficial to recover hydrogen from excess gas. There are several separation processes, based on different separation principles, namely pressure swing adsorption, polymeric membranes, and gas/liquid contacting [12].
- Converting methane to hydrogen

Hydrogen is an energy carrier and can be used as a fuel. Several processes have been developed for producing hydrogen, mainly from fossil fuels such as methane, including steam methane reforming, partial oxidation and auto-thermal reforming [13].

■ Fuel in the complex

Methane/hydrogen mixture can be added as off-gas to the fuel gas system of the plant.

Techno-economical analysis for the flare gas recovery of Amirkabir olefin plant was performed to rank these options. The results obtained are summarized in table five [10].

Table 5: Economical analysis of different methods of the flare gas recovery

Method	Total Capital Investment (million \$)	Expected Profit (million \$)	Pay Back Time (year)
Sale of the gas	-	21.4	-
Steam methane reforming	13.04	38.35	1.1
Auto thermal reforming	15.6	39.2	1.3
CH ₄ / H ₂ separation (PSA method)	13.45	26	0.5
CH ₄ / H ₂ separation (Membrane Method)	6.9	26.6	0.3
Off-gas fuel	-	1.3	-

The results are depicted in figure 4 for better comparison.

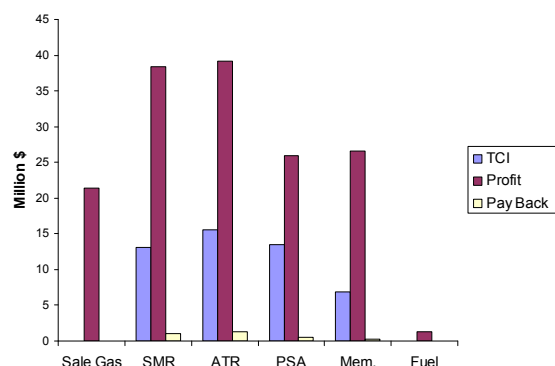


Figure 4: Economical comparison of different gas recovery methods

Sale of the gas and off-gas fuel options do not require any capital investment, therefore they could be the first priority if the company do not wish to make any investment for the flare gas recovery.

The conversion of methane to hydrogen, and methane/hydrogen separation are the second and third alternatives, respectively, considering the expected profit and pay back period.

7. SUMMARY AND CONCLUSIONS

Flares are regarded as a necessary safety device for getting rid of the excess gas produced in process industry. However, flaring also contributes to a number of environmental problems such as eco-inefficiency, resource depletion, global warming and acid deposition.

Therefore, there is growing concern to minimize flaring. Improved plant operation to decrease extra gas production which should be flared is the best approach. Otherwise, recovery of the flare gas that reduces substantially the burning of the gases is a world-wide obligation. Study of the flare gas recovery requires obtaining accurate data on the flare gas composition and flow rate.

Gas composition is generally determined by a process gas chromatograph device. Considering the characteristics of the flare gas system, such as changing flowrate and composition, large diameter gas header and safety obligations, only ultrasonic mass flow meters, which are installed in the pipe, produce reliable, accurate mass flowrate data. The ultrasonic portable devices can not produce reliable data for the flare gas system.

Indirect or soft-sensing measurements were utilized to obtain the flare gas mass flowrate. Three different indirect methods considered in this work. Results obtained from these methods are quite similar which proves the applicability of the soft-sensor measurements for this purpose.

Investigation revealed that the flare gas recovery unit is not needed for this case. Techno-economical analysis was carried out to find the best applications of the recovered flare gas. Four scenarios were discussed, and priorities were specified based on the investments needed. Selling the recovered gas without any further investment is the best choice, if the company does not wish to make any investment; otherwise, the conversion of methane to hydrogen, and selling pure hydrogen is the best option.

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