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Reducing Energy Consumption and GHG Emission by Integration of Flare Gas with Fuel Gas Network in Refinery

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***Abstract*—**Gas flaring is one of the most GHG emitting sources in the oil and gas industries. It is also a major way for wasting such an energy that could be better utilized and even generates revenue. Minimize flaring is an effective approach for reducing GHG emissions and also conserving energy in flaring systems. Integrating waste and flared gases into the fuel gas networks (FGN) of refineries is an efficient tool. A fuel gas network collects fuel gases from various source streams and mixes them in an optimal manner, and supplies them to different fuel sinks such as furnaces, boilers, turbines, etc. In this article we use fuel gas network model proposed by Hasan et al. as a base model and modify some of its features and add constraints on emission pollution by gas flaring to reduce GHG emissions as possible. Results for a refinery case study showed that integration of flare gas stream with waste and natural gas streams to construct an optimal FGN can significantly reduce total annualized cost and flaring emissions.

***Keywords*—**Flaring, Fuel gas network, GHG emissions.

I. INTRODUCTION

FLARING of waste and unwanted gases to the atmosphere is one of the major concerns in whole petroleum industry. According to the recent data from satellites, 139 billion cubic meters of gas are flared annually [1], which is equal to 4.6% of world natural gas consumption of total 3011 billion cubic meters in 2008 [2]. This results approximately 281 million tones of CO_2 emissions annually [3]. Meanwhile energy is one the most significant concerns in the world. Global energy demand is predicted to increase by 57% from 2004 to 2030 [4]. Over 40% of the operating cost of a chemical plant is contributed from energy [5]. Thus a systematic network which can utilize waste and flare gases as fuel for being consumed in the fuel gas sinks such as turbines, furnaces, boilers, is an efficient tool for saving energy and reducing GHG emissions.

A fuel gas network collects various waste gases, flare gases, and fuel gases as source streams and passes through pipelines, valves, heaters, coolers, and compressors to mix them in efficient proportions and supply them to various fuel sinks. Hasan et al called this network a fuel gas network [6]. Hasan et al. did not consider environmental constraints on his proposed model. We use his proposed model as a base model and develop new constraint for flaring emissions, which mostly is considered as CO_2 emissions, and apply the modified model on a refinery case study.

II. PROBLEM STATEMENT AND MODEL FORMULATION

A typical FGN introduced by Hasan et al. [6] consists of three main nodes (Fig. 1). The first node consists all available fuel gas sources (i =1, 2, …, I). A source is kind of a gas stream which has nonzero heating value and potential for mass balance. The waste/purge gas streams from different units in refineries such as Crude Distillation Unit (CDU), amine unit, or visbreaker unit, feed/byproduct/product gas streams such as LPG in refineries, and external fuel gasses such as natural gas which are purchased, are some examples of source streams.

The second node consists J pools that are used as mixing headers (j=1, 2, …, J). These pools are used to receive and mix fuel gas streams from different sources and send to different sinks to satisfy their requirements. Although different source streams that enter to these pools can have different temperatures, should be in the same pressure.

The third node consists K sinks where fuel gas streams are used (k=1, 2, …, K). A sink is any equipment or plant which needs fuel gas stream for producing heat or work. There are different kind of sinks such as turbines, furnaces, boilers and flares. Some sinks that have fixed energy need are defined as fixed sinks such as gas turbine drivers. In contrast sinks that can consume more fuel gas to produce power or heat over their energy need are defined as flexible sinks such as steam generating boilers.

Fig. 1 shows the superstructure of the fuel gas network. As illustrated, source stream i entering to the network will be divided by splitters. Each substream passes through auxiliary equipments (cooler, heater, compressor, and valve) and connects to header k. Each header transmits the mixture of substreams to the sink k.

The problem will be formulated with the following considerations. Within these data given:

(1) a set of source streams with known characteristics such as compositions, temperatures, pressures, and etc,
(2) a set of fuel sinks with known energy need and known acceptable range for different specifications such as flows, compositions, pressures, temperatures, lower heating value (LHV), Wobbe Index (WI).

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(3) operating and capital cost parameters for equipments used in the fuel gas network.

We assume that

(1) plant operates in the steady state condition and no chemical reaction reacts
(2) no temperature dependency for lower heating value of fuel gases
(3) only valves are used for expansions and all expansions obey Joule-Thompson expansion theory
(4) gas compressions are adiabatic and single stage
(5) no pressure drop in equipments and pipes
(6) unlimited utility operation at any temperature
(7) reference temperature and pressure are 68°F and 14.7 psia.

It is desired to determine a network that distributes fuel gas source streams to fuel gas sinks with known characteristics through auxiliary equipments with known duties. All stream specifications such as pressure, temperature, and flow should be calculated.

The goal of the problem will be achieved by minimization of total annualized cost of the fuel gas network. Capital costs of the network equipments and operating costs of the fuels and equipments and environmental costs due flaring are included in the total annualized cost.

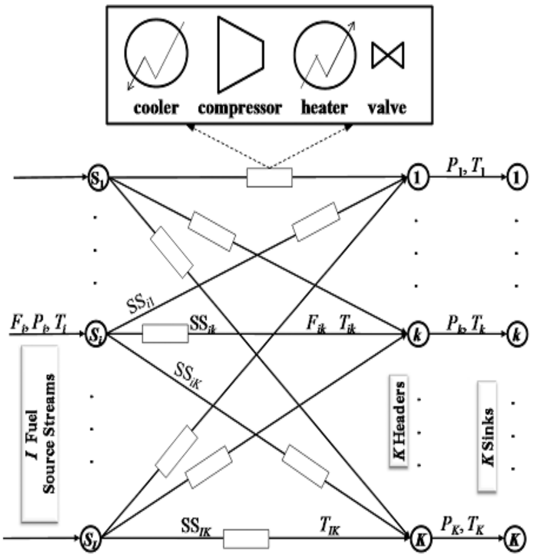

Fig. 1 Schematic superstructure of a fuel gas network

Now we can formulate the fuel gas network model with the following constraints on the flow rates, energy need of sinks, limits of temperature, pressure and fuel quality, and environmental regulation limitations.

Fuel gas flow in substream SS_{ik} is f_{ik}. F_i is the available flow of source stream *i* that can be used.

$$\sum_{k=1}^{k} f_{ik} = F_i \tag{1}$$

Source flow of valuable fuel gas streams is limited by the following constraint, where F_i^L and F_i^U are the minimum and maximum flow rate of source i.

$$F_i^L \leq F_i \leq F_i^U \tag{2}$$

Constraint (2) will change for the valuable fuel gases as below to ensure that all amount of waste/ purge gases will be consumed.

$$F_i^L = F_i = F_i^U \tag{3}$$

Flow limits of sink k (F_k^L, F_k^U) restricts the flow that is received by itself.

$$F_k^L \leq \sum_{i=1}^{I} f_{ik} \leq F_k^U \tag{4}$$

The following constraints will be used for energy needs (D_k) of fixed and flexible sinks.

$$\sum_{i=1}^{I} f_{ik} LHV_i = D_k \ (for\ fixed\ sinks) \tag{5a}$$

$$\sum_{i=1}^{I} f_{ik} LHV_i \geq D_k \ (for\ flexible\ sinks) \tag{5b}$$

As the operation in the fuel gas network is non-isothermal and non-isobaric, energy balance through the network is expressed in enthalpy change terms. h_{ik} is the heat content of the fuel gas stream that passes from source i to sink k. It is calculated as the initial enthalpy of source gas stream $(Cp_i T_i f_{ik})$ plus enthalpy change through compressor (Δh_{ik}^B), valve (Δh_{ik}^V), heater (Δh_{ik}^H), and cooler (Δh_{ik}^C).

$$h_{ik} = Cp_i T_i f_{ik} + \Delta h_{ik}^B - \Delta h_{ik}^V + \Delta h_{ik}^H - \Delta h_{ik}^C \tag{6}$$

Across the valve enthalpy change is calculated as below where μ_i, P_i, and P_k are joule-Thompson coefficient, pressure of source stream *i*, and pressure of sink *k*, respectively.

$$\Delta h_{ik}^V \geq \mu_i Cp_i f_{ik}(P_i - P_k) \tag{7}$$

Enthalpy change across the compressor where η_i is the adiabatic compression efficiency and n_i is the adiabatic compression coefficient $(\frac{R}{Cp_i})$ is

$$\Delta h_{ik}^B \geq \frac{(Cp_i T_i f_{ik} - \Delta h_{ik}^C)}{\eta_i} \left(\left(\frac{P_k}{P_i} \right)^{n_i} - 1 \right) \tag{8}$$

Constraint (9) limits the pressure of sink *k* to the acceptable range (P_k^L, P_k^L)

$$P_k^L \leq P_k \leq P_k^U \tag{9}$$

Acceptable Enthalpy range of source *i* is limited by (10) and (11), where T_i^L, T_i^U are the lower and upper allowable temperature of source *i*.

$$h_{ik} \leq Cp_i T_i^U f_{ik} \tag{10}$$

$$Cp_i T_i f_{ik} - \Delta h_{ik}^V - \Delta h_{ik}^C \geq Cp_i T_i^L f_{ik} \Delta h_{ik}^V \tag{11}$$

For the mixing header k, the enthalpy balance is as below, where T_k is the temperature of sink k and T_k^L, T_k^U are the allowable bounds of sink k temperature.

$$T_k \sum_{i=1}^{I} Cp_i f_{ik} = \sum_{i=1}^{I} h_{ik} \tag{12}$$

$$T_k^L \leq T_k \leq T_k^U \tag{13}$$

Enthalpy changes are the non-negative variables. In case of existence of equipment, variables are positive otherwise they are zero.

$$\begin{gathered} \Delta h_{ik}^B \geq 0 \\ \Delta h_{ik}^V \geq 0 \\ \Delta h_{ik}^H \geq 0 \\ \Delta h_{ik}^C \geq 0 \end{gathered} \tag{14}$$

There are some fuel quality specifications that should be considered for sinks. Specific gravity (SG) which is the ratio of the density of a gas to the air is controlled by (15). For an ideal gas specific gravity is the ratio of the gas molecular weight to the air molecular weight.

$$\sum_{i=1}^{I} f_{ik} SG_i = SG_k \sum_{i=1}^{I} f_{ik} \tag{15}$$

Constraint (16) restricts the specific gravity limits of sink k.

$$SG_k^L \leq SG_k \leq SG_k^U \tag{16}$$

Lower heating value which shows the energy content of a fuel gas is an important fuel quality specification for sinks [7]. Constraint (17) calculates the LHV of the sink k and (18) controls it between allowable range of LHV for sink k.

$$\sum_{i=1}^{I} f_{ik} LHV_i \geq LHV_k \sum_{i=1}^{I} f_{ik} \tag{17}$$

$$LHV_k^L \leq LHV_k \leq LHV_k^U \tag{18}$$

While LHV measures the heat content of a fuel gas, Wobbe Index (WI) declares the interchangeability and energy flow of a fuel gas. Constraint (20) keeps WI between its allowable limits [8].

$$WI = \frac{LHV}{\sqrt{SG}} \tag{19}$$

$$(WI_k^L)^2 SG_k \leq (LHV_k)^2 \leq (WI_k^U)^2 SG_k \tag{20}$$

The methane number (MN) which usually used for gas turbines, measures the knock resistance of a fuel gas [9]. q_i is the mole fraction of alkane composition in the fuel gas source stream i.

$$\begin{aligned} 0.242 \sum_{i=1}^{I} f_{ik} q_{i,CH_4} \geq 1.516 \sum_{i=1}^{I} f_{ik} q_{i,C_2H_6} + 3.274 \sum_{i=1}^{I} f_{ik} q_{i,C_3H_8} \\ + 5.032 \sum_{i=1}^{I} f_{ik} q_{i,C_4H_{10}} + 6.76 \sum_{i=1}^{I} f_{ik} q_{i,C_5H_{12}} \\ + 8.548 \sum_{i=1}^{I} f_{ik} q_{i,C^{5+}} \end{aligned} \tag{21}$$

Constraints (22) and (23) set the temperature of network over the moisture dew point (MDP) and hydrocarbon dew point (HDP) for restraining condensation [10].

$$\left(MDP_k + \frac{5}{9}\left(5.15 \left(\frac{P_k}{100} \right) - 312 \right) \right) \leq T_k \tag{22}$$

$$\left(HDP_k + \frac{5}{9}\left(2.33 \left(\frac{P_k}{100} \right)^2 - 1.8 \left(\frac{P_k}{100} \right) - 305 \right) \right) \leq T_k \tag{23}$$

CO_2 emission from petrochemical plants and refineries can be calculated from the below relation extracted from Title-40 of Code of Federal Regulations (CFR-40) [10].

$$CO_2 = 0.98 \times 0.001 \times \left(\sum_i^n \left[\frac{44}{12} \times (Flare)_i \times \frac{MW_i}{MVC} \times CC_i \right] \right) \tag{24}$$

Note that:

CO_2 = CO_2 emissions (metric tons/year)

Flare = volume of source gas i flared (m^3/yr)

CC_i = carbon content of flare gas (kg of carbon/kg of fuel)

MW_i = molecular weight of flare gas

MVC = molar volume conversion factor (849.5 scf/kgmole for STP of 20°C and 1 atmosphere, or 24.06 m^3/kgmole for STP of 20°C and 1 atmosphere)

44/12 = ratio of molecular weights, CO_2 to carbon

0.001 = conversion factor, kg to metric tons

Constraint (25) calculates the total CO_2 emissions from different fuel gas sources in the flare sink.

$$hc_k \geq 0.98 \times \sum_{i=1}^{I} \frac{44}{12} \times CC_i \times f_{ik} \times \frac{MW_i}{MVC} \tag{25}$$

Note that emission fee for hc_k will be imposed in the objective function.

Finally, we write our objective function which is total annualized cost as below

$$\begin{aligned} TAC = af \Bigg(& \sum_{i=1}^{I}\sum_{k=1}^{K} CC_{ik}^P f_{ik} + \sum_{i=1}^{I}\sum_{k=1}^{K} CC_{ik}^V \Delta h_{ik}^V + \sum_{i=1}^{I}\sum_{k=1}^{K} CC_{ik}^B \Delta h_{ik}^B + \sum_{i=1}^{I}\sum_{k=1}^{K} CC_{ik}^H \Delta h_{ik}^H \\ & + \sum_{i=1}^{I}\sum_{k=1}^{K} CC_{ik}^C \Delta h_{ik}^C \Bigg) + OPH \\ & * \left(\sum_{i=1}^{I} \alpha_i F_i + \sum_{k=1}^{K} \nu_k \left(\sum_{i=1}^{I} f_{ik} tc_i \right) \right. \\ & + \sum_{k=1}^{K} \gamma_k hc_k - \sum_{k=1}^{K} \beta_k \left(\sum_{i=1}^{I} LHV_i f_{ik} - D_k \right) \\ & + \sum_{i=1}^{I}\sum_{k=1}^{K} OC_{ik}^P f_{ik} + \sum_{i=1}^{I}\sum_{k=1}^{K} OC_{ik}^V \Delta h_{ik}^V \\ & \left. + \sum_{i=1}^{I}\sum_{k=1}^{K} OC_{ik}^B \Delta h_{ik}^B + \sum_{i=1}^{I}\sum_{k=1}^{K} OC_{ik}^H \Delta h_{ik}^H + \sum_{i=1}^{I}\sum_{k=1}^{K} OC_{ik}^C \Delta h_{ik}^C \right) \end{aligned}$$

where the first five terms are capital cost for pipes, valves, compressor, heater, and cooler. The other terms are operating cost including cost of fuel gases, treatment cost, CO_2 emission penalty, revenue from flexible sinks and equipment operating costs. The cost parameters are as follows: af is the annualization factor, CC_{ik} is the equipment capital cost, OPH is the operating hours per year, α_i is the fuel gas cost, ν_k is the treatment factor for sink k, tc_i is the treatment cost for source i, γ_k is the CO_2 emission penalty by flaring, β_k is the revenue from flexible sink, OC_{ik} is the equipment operating cost.

Now we have completed our NLP model formulation. The model is solved using BARON solver in GAMS 23.5.

III. CASE STUDY

We apply our modified model to a refinery case study. This refinery has five source streams and a flare stream which we want to integrate it with other source streams to make an optimum fuel gas network.S1-S4 are waste gas streams from different units in the refinery, S5 is natural gas which is a external fuel gas and we wish to consume as low as possible and FS is the stream which normally is flared. Our case study has nine fuel sinks.

C1-C7 are furnaces in different units, C8 is boilers and C9 is flare sink. Tables I and II show the data and parameters of sources and sinks. Table III represents the cost parameters for different equipments [11]. We consider 10% of annualization factor and 8000 hours working time for plant.

We solved our model to obtain the optimal network. Tables IV and V show the flow distribution from sources to sinks and variable values in sinks. From Table V, we can see all model variables are in the allowable range of sinks.

Note that our optimal FGN just uses valves and other equipments are not required in this case. Total annualized cost for this case is $79,802,440 which includes $79,198,420 for operating cost and $604,020 for capital costs. Natural gas fuel cost plays a significant part in operating costs. We consider a base scenario, to calculate savings from the optimal FGN, which natural gas is the only source stream and other waste gases are normally sent to flare.

TABLE I
DATA AND PARAMETERS FOR SOURCES

Specification/Parameter	S1	S2	S3	S4	S5	FS
flow (m^3/hr)	5116	4934	8355	8699	<90000	6980
temperature (K)	318	318	311	322	318	318
pressure (psia)	68	360	355	65	450	68
Cp (kJ/m^3.k)	2.19	1.42	1.25	1.6	1.6	2.35
adiabatic efficiency	0.75	0.75	0.75	0.75	0.75	0.75
adiabatic compression coefficient	0.16	0.24	0.26	0.22	0.20	0.18
LHV (MJ/m^3)	54.89	23.35	16.43	31.59	40.68	41.03
SG	0.89	0.32	0.18	0.46	0.64	0.66
carbon content (kg of carbon/kg of fuel gas)	1.08	0.28	0.14	0.48	0.76	0.77
methane (mol %)	22	8	3	9	87	10.5
ethane (mol %)	18	11	3	11	8	31.6
propane (mol %)	16	3	0.2	7.2	3.5	2.1
butane (mol %)	14	1.5	0.8	2.8	1.5	10.5
C5+(mol %)	2	0.5	2	3	0	0
hydrogen (mol %)	28	76	91	67	0	45.3
sulfur	0	0	0	0	0	0
H_2S (ppm)	0	0	0	0	0	0
treatment cost ($/Mscf)	1.75	0	0	0	0	1.75
price ($/MMscf)	0	0	0	0	5000	0

TABLE II
CAPITAL AND OPERATING COST PARAMETERS FOR EQUIPMENTS

Equipment	Capital cost($/kW)	Operating cost($/kWh)
compressor	100000	0.1
heater	50000	0.01
cooler	50000	0.02
valve	5000	0.001

Detailed economic data are given in Table VI. As the results indicates integration of flare gas stream to fuel gas network saves $30,637,014 (27.7%). Also natural gas consumption has reduced to 51786 m^3/hr which shows 31.6% reduction. And annual emission penalty by flaring shows 90.6% reduction due to utilization waste and flare streams.

TABLE III
DATA AND PARAMETERS FOR SINKS

Specification/Parameter	C1	C2	C3	C4	C5	C6	C7	C8	C9
flow range (m^3/hr)	12000-25000	1500-4000	4000-9500	3000-6000	4000-9000	4-15	40-150	25000-45000	≥0
temperature (K)	273-800	273-800	273-800	273-800	273-800	273-800	273-800	273-800	273-800
pressure (psia)	25-360	25-360	25-360	25-360	25-360	25-360	25-360	25-360	25-360
demand (MJ/s)	183.2	32.8	93.8	50.1	69.3	0.1	0.9	434.2	≥24.2
WI	40-110	40-110	40-110	40-110	40-110	40-110	40-110	40-110	-
MDP (K)	277	277	277	277	277	277	277	277	-
HDP (K)	277	277	277	277	277	277	277	277	-
LHV (MJ/m^3)	30-100	30-100	30-100	30-100	30-100	30-100	30-100	30-100	12-100
SG	0.4-1	0.4-1	0.4-1	0.4-1	0.4-1	0.4-1	0.4-1	0.4-1	0.4-1
sulfur	-	-	-	-	-	-	-	-	-
H_2S	<150	<150	<150	<150	<150	<150	<150	<150	<150
treatment factor	1	1	1	1	1	1	1	1	1

TABLE IV
FLOW DISTRIBUTION FROM SOURCES TO SINKS

	Sinks								
Sources	C1	C2	C3	C4	C5	C6	C7	C8	C9
FS	297	0	0	4395.8	2208.2	0	79	0	0
S1	3499	396.8	0	0	1220.2	0	0	0	0
S2	674.5	0	1227.3	0	0	0	0	3032.2	0
S3	4480.4	0	0	0	0	0	0	3199.5	675.1
S4	254.9	3048.4	0	0	2909.2	11.4	0	0	2475.1
S5	8797	0	7597	0	0	0	0	35392	0
Total	18002.8	3445.2	8824.3	4395.8	6337.6	11.4	79	41623.7	3150.2

TABLE V
VARIABLE VALUES IN SINKS

	Temperature (K)	Pressure (Psia)	SG	LHV (MJ/m^3)	WI (MJ/m^3)
C1	309.1	60	0.56	36.6	48.9
C2	321.3	60	0.51	34.3	48
C3	315.6	360	0.59	38.3	49.6
C4	318	68	0.66	41	50.5
C5	319.3	60	0.61	39.4	50.3
C6	320.9	28.5	0.46	31.6	46.6
C7	318	68	0.66	41	50.5
C8	315.1	355	0.58	37.5	49.2
C9	317.1	17	0.40	28.3	44.8

TABLE VI
ECONOMIC DATA OF COMPARISON BETWEEN 2 SCENARIOS

Scenario	Natural gas consumption, (m^3/hr)	TAC ($/yr)	Capital Cost ($)	Operating Cost ($/yr)	flaring amount (m^3/hr)	flaring emission penalty, ($/yr)
No FGN	78691	110439454	-	-	29299	6404894
Integration of flare gas stream with FGN	51786	79802440	604020	79198420	3151	599559

IV. CONCLUSION

In this work, we integrated flared stream gas to the fuel gas network with waste and fuel gas streams. We modified the base fuel gas network model proposed by Hasan et al. [6] adding constraints in CO_2 emissions by flaring. This term in total annualized cost can help to reduce GHG emissions and flaring penalties as much as possible. The refinery case study proved that by utilizing flared gas stream to the network, our optimal FGN can reduce energy costs and flaring emissions.

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