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Power Consumption Minimization of Khormoj Compressor Station

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Abstract

Arguably, the natural gas transmission pipeline infrastructure in Iran represents one of the largest and most complex mechanical systems in the world. The optimization of large gas trunk lines known as IGAT results in reduced fuel consumption or higher capability and improves pipeline operation. In the current study, a single-objective optimization was conducted for Khormoj compressor station on the Iranian gas trunk line V (IGAT5). The system consists of over 504 kilometers of 56-inch pipeline from South Pars to Aghajari. This system passes through a tortuous terrain with changes in elevation which makes the optimization process even more challenging. Genetic algorithm (GA) was used in this optimization along with detailed models of the performance characteristics of compressors. The results show that in stations having the same compressor in parallel the minimum power (energy) consumption is reached when split flow in all the compressors is the same.

Keywords: Compressor Station, Single and Multi-objective Optimization, Genetic Algorithm

1. Introduction

Nowadays, the continual and indiscriminate increase in the price of oil, coupled with the significant decline in reserves, as well as the new environmental attitude expressed by various national governments about the existing high levels of air pollution have led to the exploitation of a cleaner and more economically attractive fuel, namely the natural gas.

A principal component of any gas transmission system is the compressor station. A given system may have from a few up to well over 50 stations anywhere in the pipeline. These stations add enough energy to the gas to overcome frictional losses and to maintain required delivery pressures and flows. Fuel and power costs for compressor operation approach a staggering half a billion dollars per year in the United States alone. Every 1% in fuel savings represents up to 5 million dollars per year in economic benefits.

Iran holds the second largest gas reserves in the world with over 27.5 trillion cubic meters (TCM) of natural gas. Gas can be utilized as a feed stock in petrochemical plants and refineries or exported through pipeline or liquefied natural gas (LNG). Through the re-injection of gas to oil reservoirs, while increasing the oil recovery ratios, the produced gases from fields shared with other countries could be stored into domestic gas fields.

IGAT V is designed to move sour gas from the huge gas reservoir of the South Pars field (Iranian off-shore), which is located in the south of Iran, (see Figure 1) to Aghajari.

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The initial volume for the transmission of sour gas is approximately 75 MMSCMD. The gas production will be transmitted through a 504-kilometer 56-inche pipeline from South Pars to Aghajari. There will be five compressor stations installed on the route of the pipeline including 2 stations in the South Pars and 3 stations in the cities of Khormoj, Abpakhsh, and Sardasht.

Figure 1
Iranian nationwide gas transfer pipelines (IGAT5).

There have been lots of researches on the optimization of gas transmission systems in the world. Edgar et al (1988) used both nonlinear programming (NLP) and branch and bound scheme for the optimal design of gas transmission systems. Osiadacz (1994) used hierarchical system theory for the dynamic optimization of high-pressure gas networks. Wolf and Smeers (2000) employed mixed integer nonlinear programming known as MINLP for fuel cost minimization. Tabkhi (2007) applied MNLP to the optimum design and fuel consumption minimization of gas transmission networks. Chebuba et al (2009) applied ant colony optimization (ACO) to fuel consumption minimization problem in natural gas transportation systems for the first time. For gas pipeline operation optimization the ant colony algorithm is a new evolutionary optimization method.

This paper presents the application of genetic algorithm (GA) methodologies to the single-objective optimization of four similar units from a compressor station on the 5th major gas transmission pipeline of the National Iranian Gas Company (NIGC), i.e. IGAT5, which is driven by similar gas turbine as well as four coolers of the same size with the familiar constraints of booster compressor operating boundaries, gas turbine performance limits, and climatic conditions. The results include single-objective optimization with GA to minimize power consumption for a given throughput.

2. Governing equations

2.1. Hydraulic equations for gas pipeline

In general, the hydraulic equations of a pipeline consist of three important equations as follows:
1-Conservation of mass equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x}(\rho v)=0 \tag{1}$$

2-Conservation of momentum equation:

$$\frac{\partial}{\partial t}(\rho v)=-\frac{\partial}{\partial x}\left(P+\rho v^{2}\right)-\rho f \frac{2v|v|}{D}-\rho g \sin\theta \tag{2}$$

3-Conservation of energy equation:
One of the usual models of energy equation which presents the explicit relation of functionality of this equation to the temperature is given by:

$$\left(\frac{\partial T}{\partial t}\right)+v\left(\frac{\partial T}{\partial x}\right)+\frac{V_w^2}{c_p}\left[1+\frac{T}{z}\left(\frac{\partial z}{\partial T}\right)_P\right]\left(\frac{\partial v}{\partial x}\right)=\frac{V_w^2}{c_p P}\left[1-\frac{P}{z}\left(\frac{\partial z}{\partial p}\right)_T\right]\frac{\Phi+wv}{A} \tag{3}$$

where, c_p is the heat capacity of fluid in constant pressure and z stands for compressibility factor; V_w represents noise velocity in the operation condition of problem.
The hydraulic equations for a pipeline with a fixed section area are defined by considering the following assumptions:

1- The flow is homogenous and isothermal;
2- The flow direction is parallel to the pipe axis;
3- In every section of pipeline, the flow is homogenous and isothermal;

Assumptions 2 and 3 imply that the flow is assumed one dimensional during transmission line.
By differentiating mass and momentum equations in steady state and doing some combinations and simplification, the equation of pressure-flow will be obtained. Therefore, the general equation of flow by omitting the kinetic energy term reads:

$$Q_b = A_1\left(\frac{T_b}{P_b}\right)\left[\frac{P_1^2-P_2^2-f\left(\Delta H\right)}{gLT_{avg}z_{avg}}\right]^{\frac{1}{2}}\sqrt{\frac{1}{f}}\times D^{2.5} \tag{4}$$

To use the above equations to calculate the flow rate or pressure friction factor is required. Lots of empirical equations such as Panhandle-B, Colebrook-White, Weymouth, AGA, and Panhandle A are suggested to find friction factor.

2.2. Modeling of main equipment of compressor station

a. Compressor

Compressors are governed by the following equation to calculate head:

$$H = C\frac{T_s\, z}{\left(\frac{K-1}{K}\right)g}\left[\left(\frac{P_d}{P_s}\right)^{\left(\frac{K-1}{K}\right)} - 1\right] \tag{5}$$

Discharge temperature is expressed as follows:

$$T_d = T_S + \frac{T_S\left(\frac{z_s + z_d}{2}\right)}{\eta_{id}}\left[\left(\frac{P_d}{P_S}\right)^{\left(\frac{K-1}{K}\right)} - 1\right] \tag{6}$$

a.1. Centrifugal compressors

For centrifugal compressors, there is a performance curve in which head, power, or efficiency is drawn according to the flow rate at different revolutions per minute or compressor speeds (N_r). If performance curves are entered, a polynomial fit of the curves is done so that:

$$\frac{H}{N_r^2} = b_1 + b_2\left(\frac{Q_{ac}}{N_r}\right) + b_3\left(\frac{Q_{ac}}{N_r}\right)^2 + b_4\left(\frac{Q_{ac}}{N_r}\right)^3 \tag{7}$$

$$\eta_{id} = b_5 + b_6\left(\frac{Q_{ac}}{N_r}\right) + b_7\left(\frac{Q_{ac}}{N_r}\right)^2 + b_8\left(\frac{Q_{ac}}{N_r}\right)^3 \tag{8}$$

a.2. Fuel consumption

To find the fuel consumption needed for producing the required power of the compressors, one may refer to the below equation:

$$\dot{m}_f = \frac{Power}{LHV \times \eta_{dr}} \quad \dot{m}_f = \frac{Power}{LHV \times \eta_{dr}} \tag{9}$$

where, η_{dr} is the compressor driver efficiency or mechanical efficiency of turbine.

3. Optimization

The optimization of chemical processes has been known from a long time; the limitation of energy resources and their increasing use in various industries make optimization seem even more important. In other words, the reasonable consumption of raw materials and energy in order to optimize the efficiency is the optimization objectives.

3.1. Overview of optimization

Optimization is the act of obtaining the best result under given circumstances. The ultimate goal of all decisions is either to minimize the effort required or to maximize the desired benefit. Without loss of generality, optimization can be taken to mean minimization since the maximum of a function can be found by seeking the minimum of the negative of the same function (Figure 2).

This paper presents the application of GA methodologies to the single-objective optimization of four similar units from a compressor station driven by a similar gas turbine as well as four coolers of the same size (one of the units is turned off; thus, as a matter of fact, we deal with 3 compressor units--3+1). The single-objective optimization using GA results in 6 decision variables and an optimization space of 8589934592 cases.

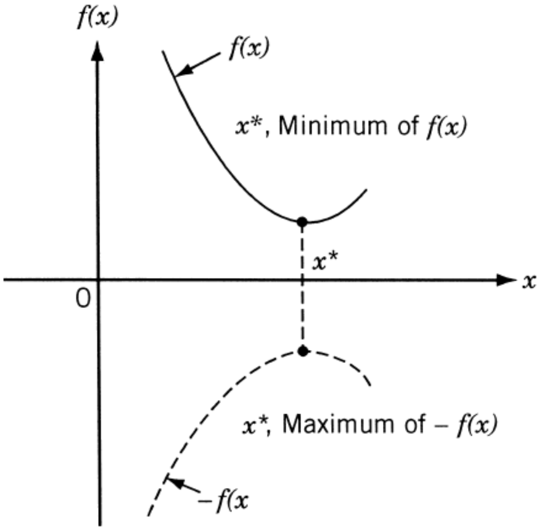


Figure 2
Minimum of *f*(*x*) is the same as the maximum of −*f*(*x*).

4. Compression power train system

National Iranian Oil Company (NIOC) intends to develop the offshore and onshore facilities of the South Pars gas field located 100 km offshore in the Persian Gulf to produce, treat, and transport a total of 3600 MMSCFD of reservoir fluids from three development phases,1200 MMSCFD for each phase,- on a dry basis.

The dry sour gas is transported via an almost 500-km 56-inch pipeline for the injection into the Aghajari oil reservoir (3200 MMSCFD) and to another gas refinery (400 MMSCFD). This gas refinery connection is taken down the stream of BGCS#1 (booster gas compressors system). Two gas compression stations will be provided in the onshore gas plant and three others gas compression stations will be provided along the pipeline route. The function of the booster gas compressors is to raise the pressure of the gas from the BGCS#1 to meet the inlet battery limit pressure of the Aghajari booster gas compressor station, i.e. a minimum of 70 barg.

As Table 1 shows, Khormoj compressor station comprises four similar compressors driven by four similar gas turbines and four aerial coolers of the same size which are connected in parallel to all the compressor units. Figure 3 shows a schematic of the station and the downstream pipeline section comprising the power train system considered as an example for the present optimization exercise.

Table 1
Four similar compressors.

Unit	Compressor Unit
1	SIEMENS STC-5V
2	SIEMENS STC-5V
3	SIEMENS STC-5V
4	SIEMENS STC-5V

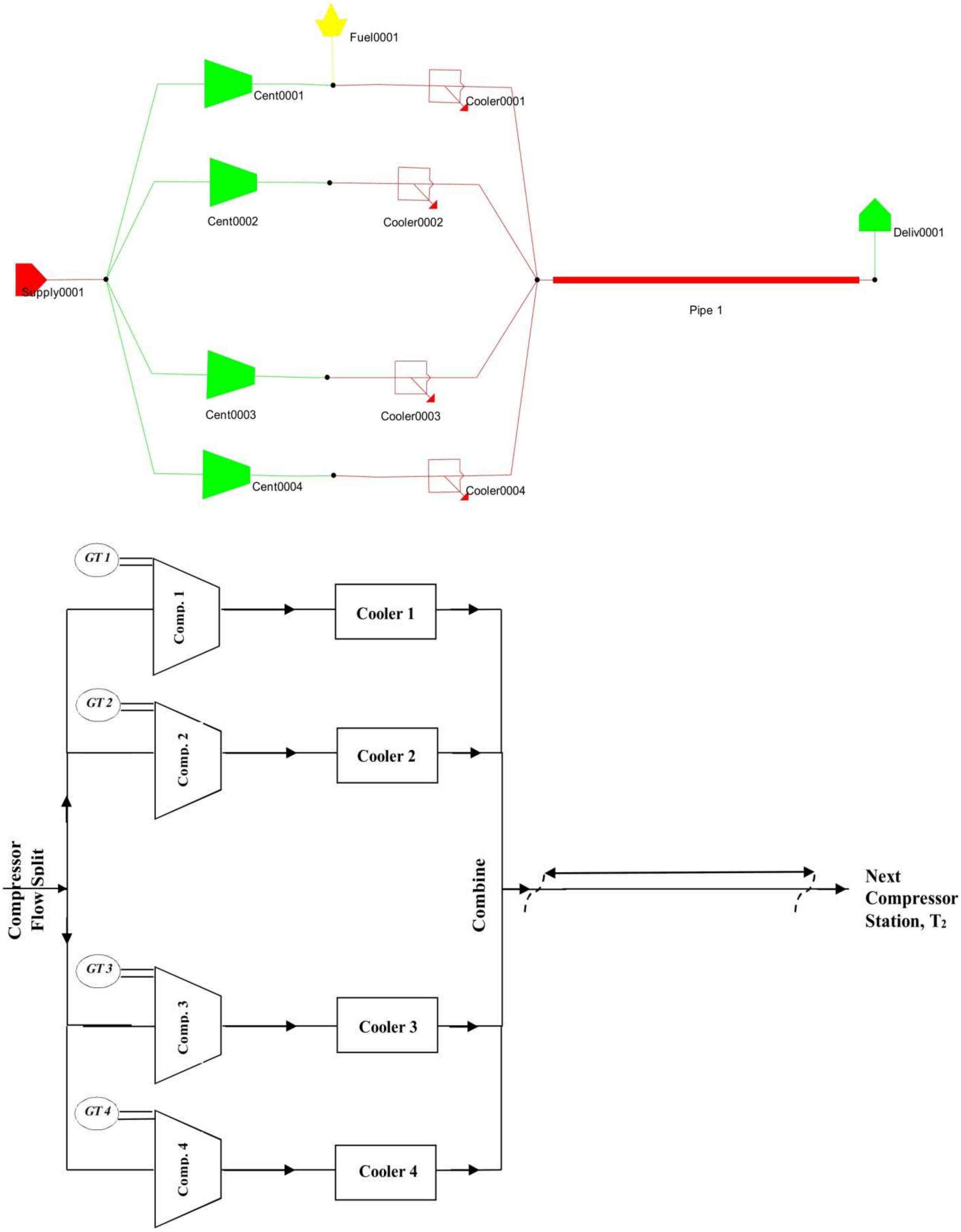


Figure 3
A schematic of the four-unit compressor.

4.1. Gas properties

The molar composition of the gas used for compressor selection is tabulated in Table 2:

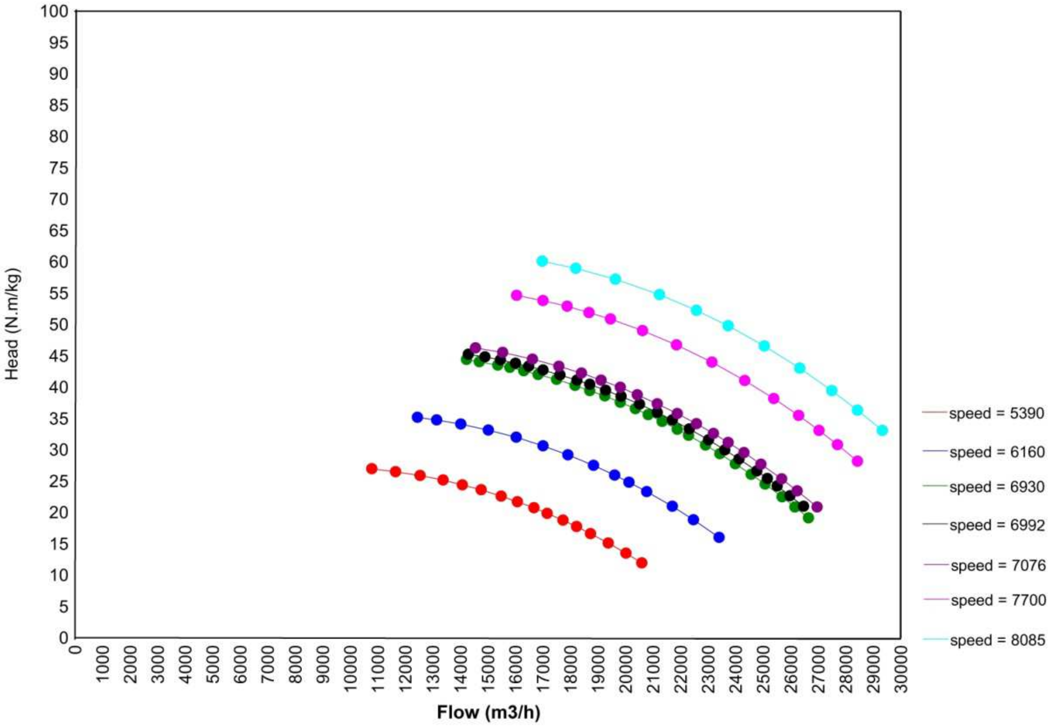
Table 2

Compositions of South Pars gas (summer)

Component	Composition	Molar fraction
1	Methane	0.880158
2	Ethane	0.055548
3	Propane	0.006097
4	i-Butane	0.000450
5	n-Butane	0.000431
6	i-Pentane	0.000027
7	n-Pentane	0.000018
8	n-Hexane	0.000001
9	Nitrogen	0.031960
10	CO_2	0.018908
11	H_2S	0.006390
12	H_2O	0.000000
13	M-Mercaptan	0.000003
14	E-Mercaptan	0.000005
15	COS	0.000004

The compressor performance characteristics and associated driver heat rate map at the ambient temperature of 90 °F are shown in Figure 4a and 4b.

a)



b)

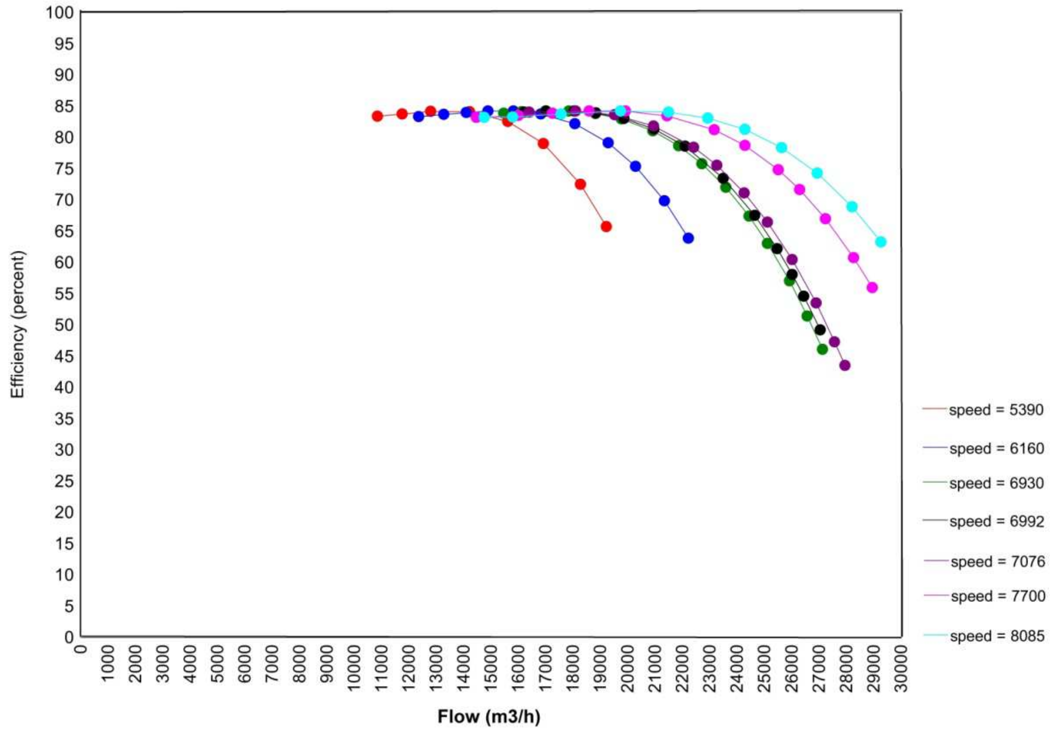


Figure 4
Performance characteristics of the compressors; a) head vs. flow; b) efficiency vs. flow.

In a single-objective optimization for a given throughput, case-specific input parameters are listed in Table 3. The case study is based on the information of the 5th major gas transmission pipeline of the National Iranian Gas Company (NIGC), i.e. IGAT 5 gas transmission pipeline. A total throughput of 3600 MMSCFD of natural gas is transported from the South Pars gas field for injection into the Aghajari oil reservoir (3200 MMSCFD) and to Fajr gas refinery (400 MMSCFD).

Table 3
Input parameters for the power train system of Figure 3.

Input parameters		
Suction pressure (P_1)	87	barg
Discharge pressure (P_2)	92	barg
Suction temperature (T_1)	45	°C
Soil temperature	10	°C
Ambient temperature	48	°C
Gas flow	3600	MMSCFD

The control variables are:

1- Compressor load sharing in terms of the volume flow split to each compressor unit;
2- Mode of the compressors (On/Off).

For this work, because of the non-continuous nature of variable 2, gradient-based methods cannot be used. Therefore, a single-objective genetic algorithm (GA) was used the operators of which are tabulated in Table 4.

Table 4

Genetic Operators.

Genetic	
Population size	20
Elitism	2%
Directional crossover	80%
Classical crossover	30%

Table 5 gives the selected resolution for each of the above control variables, the range, and the corresponding required number of GA strings. It is shown that for such a single-objective exercise the total number of GA strings is 33 and the resulting search space is 8589934592. It should be noted that the minimum and maximum of compressor flow split are defined according to surge and stonewall lines.

Table 5

Control variables in case of single-objective optimizations with GA.

Control variable	Min	Max	Resolution	Number of cases	Number of string
Compressor flow split (fraction to compressor Cent0001)	0.15	0.55	0.001	401	9
Compressor flow split (fraction to compressor Cent0002)	0.15	0.55	0.001	401	9
Compressor flow split (fraction to compressor Cent0003)	0.15	0.55	0.001	401	9
Compressor 1 status				2	2
Compressor 2 status				2	2
Compressor 3 status				2	2
Total string length					33
Design space					8589934592

A custom-built computer program (simulator) is used as a simulator for modeling the compressor station described above. The model simulates the steady-state gas flow from the suction to the compressors and finally to the discharge. The pressure drop and temperature profile along the various pipeline sections are obtained from solving the below equations:

$$\frac{dP}{dx} = -\frac{16 f\dot{m}^2}{\pi^2 \rho D_i^5} \tag{10}$$

$$\frac{dT}{dx} = -\frac{U\pi D_o}{\dot{m}C_p}\left(T - T_{soil}\right) \tag{11}$$

And AGA is used as a flow equation given by:

$$\begin{cases} Q = f\left(\Delta P\right) \\ Q_b = 0.4696\left(\frac{T_b}{P_b}\right)\left(\frac{P_1^2 - P_2^2}{gT_f z_{ave} L}\right)^{0.5}.\log\left(3.7\frac{D}{K_e}\right).D^{2.5} \end{cases} \tag{12}$$

Table 6 gives the salient specifications of aerial coolers, and their dimensionless performance characteristics in terms of pressure drop and degree of cooling are given in Figures 5 and 6. These data are used as the input to the simulator.

Table 6
Specifications of the aerial coolers.

Aerial cooler	1, 2, and 3
Type	Forced draft
Number of passes	1
Number of bays	8
Bare surface area/bay (m^2)	308.8845
Number of fans per bay	3
Fan drive type	Electric motor
Max fan speed (rpm)	180
Min fan fraction (rpm)	Full speed (100% speed)
Air flow/fan at 100% speed (kg/s)	110
Tube materials	(Carbon steel) sa-179
Fin materials	Aluminum
Tube length (mm)	12000
Fan power (design) (kW) for one fan	40
Fan power (motor) (kW) for one fan	49.5
Number of bundles of tubes per bay	2
Number of tubes per bay	400
Tube O.D. (mm)	25.4
Tube wall thickness (mm)	1.65
Tube I.D. (mm)	19.56

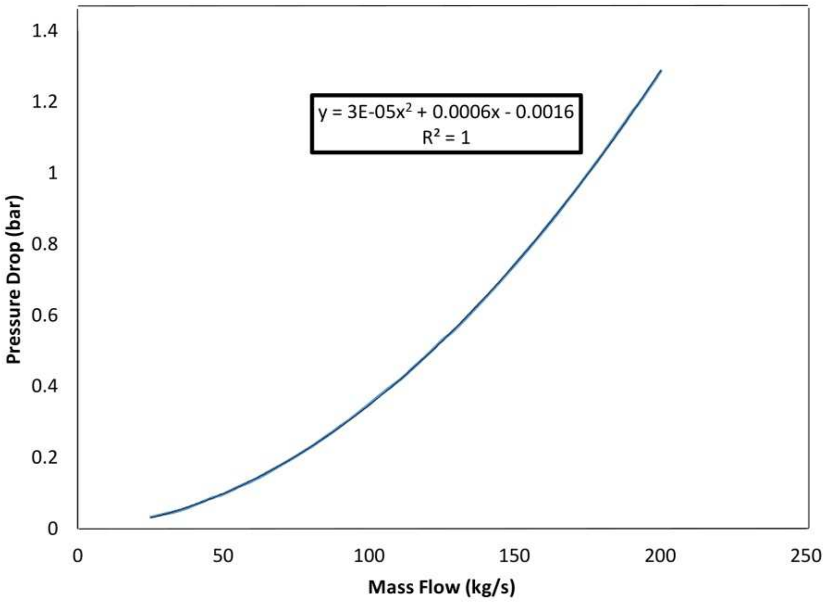


Figure 5
Pressure drop through coolers.

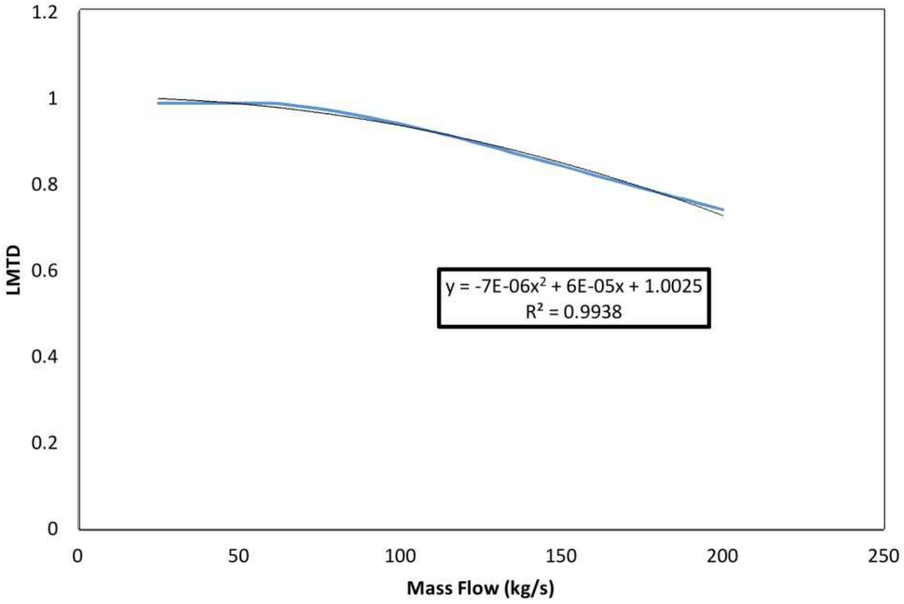


Figure 6
Dimensionless performance characteristics of coolers.

5. Results and discussion

Single-objective optimization simulations are conducted at fixed a throughout of 3600 MMSCFD with GA and the results are shown in Figure 7, where the resulting total power consumptions are plotted against the number of iterations.

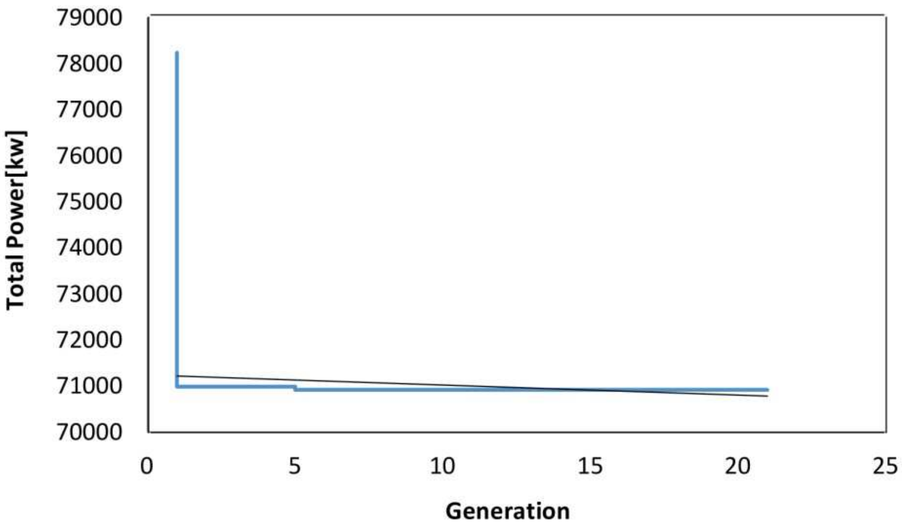


Figure 7
Results of single-objective optimizations with GA.

After 21 generations, minimum power or fuel consumptions is obtained. The variables which play an important role in this optimization are listed below along with their values.

Table 7
Results in case of single-objective optimization.

Compressor	**1**	**2**	**3**
Flow [MMSCFD]	1214.8148148148152	1214.8148148148152	1170.3703703703696
Compressor status[On/Off]	1	1	1
Load sharing (fraction to compressor)	0.337448559670782	0.337448559670782	0.325102880658436
Total power required [kW]		70918.54	

It is obvious that, in stations having the same compressor in parallel, the minimum fuel (energy) consumption is reached when split flow in all the compressors is almost the same. The minimum flow split is considered as a limit to be far from the surge zone of the compressor.

6. Conclusions

The following concluding remarks can be drawn from the present work:

1. In order to perform the optimization simulations, the optimizer engine was directly linked to a steady state pipeline simulator. A huge number of calls to the steady state simulator were performed in the process of optimization by the optimizer engine to find an optimal solution for the selected objective function. This resulted in a significant run time for the process of optimization to reach a feasible solution. The range of run time depended on many parameters and it could vary from hours to a number of days on normal high speed single-processor computers;
2. Single-objective optimization based on genetic algorithm was successfully developed for the entire power train of a multi-unit compressor station including four similar units and four identical aerial coolers which are connected in parallel to all the compressor units;
3. In stations having the same compressor in parallel, the minimum fuel (energy) consumption is reached when split flow in all the compressors is the same (load sharing is equal in all the compressors);
4. Based on the simulations done on this system, although cooling has an efficient role in power consumption minimization, it appears that most of the savings are derived from optimizing the load sharing among the parallel compressors;
5. The affects of the equipment such as valves, scrubbers, etc. are not considered in the current simulation, which should be considered for a more accurate simulation. Moreover, the detailed models of air coolers could be considered along with the seasonal temperature changes;
6. In addition to GA, some new algorithms such as bees algorithm could be used to meet the results.

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Nomenclature

MMSCMD : Million standard cubic meters per day
BCFD : Billion cubic foot per day
IGAT : Iranian gas trunk lines
MNLP : Mixed nonlinear programming
BGCS : Booster gas compressor station
LHV : Low heating value
Power : Power of turbine
ρ : Density
v : Velocity
g : Gas gravity (dimensionless)
g_c : Proportionality constant 32.2 (lb.m.ft/lbf.s^2)
c_p : Specific heat capacity at constant pressure (Btu/lb.F)
T_b : Temperature at base condition 520 °R
T : Temperature (°R)
T_{avg} : Average temperature (°R)
T_1 : Temperature of gas at the first point
T_2 : Temperature of gas at the second point
T_g : Temperature of environment (ground)
Q : Actual inlet flow rate to a compressor unit (MMSCMD)
Q_{ac} : Inlet actual volumetric flow (m^3/sec)
U : Overall heat transfer coefficient (Btu/h.ft^2.F)
Q_b : Gas flow rate at base conditions (MMSCFD or MCF/HR)
e : Total energy consumption
J : Joule Thompson effect
Ps : Suction pressure (psia)
P_d : Discharge pressure (psia)
P_b : Pressure at base condition 14.7 psia
P_1 : Gas inlet pressure to the pipeline (psia)
P_2 : Gas exit pressure (psia)
W : Compressor power (MW)
z_s : Suction compressibility factor
z_d : Discharge compressibility factor
z_{avg} : Compressibility factor at P_{avg} and T_{avg} (dimensionless)
z : Compressibility factor
N_r : Compressor speed (rpm)
D : Inside diameter of the pipeline (in)
H : Head across a compressor unit kJ/kg
η_{id} : Adiabatic efficiency
b_1, b_2, b_3,and b_4 : Head coefficients determined by polynomial fit

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