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Optimization of a Natural Gas Transmission System

J. Haddad
Gas Engineering Department
Petroleum University of Technology, Iran

R.M. Behbahani, PhD.
Gas Engineering Department.
Petroleum University of Technology, Iran

ABSTRACT
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, Single and Multi-objective optimizations were conducted for a compressor station comprising four similar compressor units driven by four similar gas turbines, four coolers of the same size and a pipeline section to the next station. This pipeline section is on the 2th major gas transmission pipeline of the National Iranian Gas Company, NIGC, or IGAT2 which is designed to move over 79 MMSCMD (2.8 BCFD) of natural gas from the Assaluyeh Gas Refinery to the ports. Genetic, Particle Swarm and SQP Algorithms were used in this optimization along with detailed modeling of the performance characteristics of compressors, aerial coolers, and downstream pipeline section. The results showed that, for stations having the same compressor in parallel, the minimum fuel (energy) consumption is reached when split flows in all compressors are the same. By the way, it can save fuel consumption in the order of 2-4 % by adjusting unit load sharing and coolers downstream temperatures slightly. It appears that most of the savings (around 70–75%) are derived from optimizing the load sharing between the four parallel compressors. Also PSO algorithm reached better and faster results than two other algorithms.

General Terms
Algorithms and Fuel optimization

Keywords
Compressor Station, Single and multi-Objective Optimization, Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Sequential Quadratic Programming (SQP).

1. INTRODUCTION
Oil and natural gas have been the most major resources of energy from past to present, as crude oil provides 33.6% and natural gas 24.2% of world energy consumption in the past year [1]. Arguably, the natural gas transmission pipeline infrastructure in the IRAN represents one of the largest and most complex mechanical systems in the world. High pressure natural gas transmission pipelines are very important because they are the most cost-effective ways for transmitting natural gas over long distances. A natural gas transmission system usually consists of receipt points, pipeline segments, compressor stations, and delivery sites. The compressor station is the principal component of any gas transmission system [2]. These stations are located along the pipeline to compensate for the pressure decrease due to friction, heat transfer and elevation losses and to maintain required delivery pressures and flows. Like case presented in this paper, most compression is powered by natural gas taken directly from the pipeline, Fuel and power costs for compressor operation approach a staggering half billion dollars per year in the United States alone. Every 1% saving in fuel consumption means up to 5 million dollars per year in economic benefits [2]. Lots of researchers have been working on optimization of gas transmission system in the world from past till now. Edgar et al (1988) used both NLP and Branch and bound scheme for optimal design of gas transmission systems [3]. Osiadacz (1994) used hierarchical system theory for Dynamic optimization of high-pressure gas networks [4]. Wolf and Smeers (2000) used Mixed integer nonlinear programming known as MINLP for fuel cost minimization [5]. Tabkhi (2007) applied MNLP for optimum design and fuel consumption minimization of gas transmission networks [6]. Chebuba et al (2009) first applied Ant Colony Optimization (ACO) for fuel consumption minimization problem in natural gas transportation systems For gas pipeline operation optimization the ant colony algorithm is a new evolutionary optimization method [7].

This paper presents application of Genetic Algorithm (GA) methodologies to multi-objective optimization of four similar units from a compressor station on the 2th major gas transmission pipeline of the National Iranian Gas Company, NIGC, or IGAT2 driven by similar gas turbine (N.P MS5002C) as well as four coolers of the same size with the familiar constraints of booster compressor operating boundaries, gas turbine performance limits. Results include single-objective optimization using SQP, GA and PSO to minimize fuel consumption for a given throughput and multi-objective optimizations of minimum fuel consumption and maximum throughput.

2. OPTIMIZATION METHODOLGY
Optimization is the procedure of detecting attributes, configurations or parameters of a system, to produce desirable responses [8]. Typically, there are three fundamental objective functions pertaining to a gas pipeline network operation. These are total energy (fuel) consumption, throughput and linepack. The present paper deals with the first two objectives by optimization of single- vs. multi-compressor unit operations. For example, optimization of the energy (fuel) consumption can be formulated as follows [9].

$$\min\left\{\sum_{r\in R} e\left(\dot{m}, P_s, P_d\right) + \sum e\left(fans\right)\right\} \tag{1}$$

Subject to the following constraints:

$$\left.\begin{array}{l} W_{r,\min} < W < W_{r,\max} \\ N_{r,\min} < N_r < N_{r,\max} \\ Surge < \left(\dfrac{Q}{N}\right)_r < Stonewall \end{array}\right\} r \in R \tag{2}$$

And other linear and non-linear constraints, where:

$$e(\dot{m}, P_s, P_d)_r = \alpha \frac{\dot{m}H}{\eta_{is}\eta_m\eta_{th}}, \forall(\dot{m}, P_s, P_d) \in D \quad (3)$$

Maximum throughput (delivery or receipt), can be Maximum throughput (delivery or receipt), can be represented by:

$$\max\left\{\sum_{k=1}^{N_D} Q_k\right\}; \max\left\{\sum_{k=1}^{N_R} Q_k\right\} \quad (4)$$

Basically, optimization methods can be classified into two categories: gradient based methods and stochastic methods. Gradient based methods rely on the derivative of the function being optimized with respect to all control variables that define the system. There are several gradient-based optimization methods depending on the nature of the objective function and associated constraints, i.e. constrained and unconstrained linear, quadratic and non-linear programming. In this research, Sequential Quadratic Programming (Constrained Nonlinear Optimization Algorithm - fmincon SQP Algorithm) is used. In addition, stochastic methods, Particle Swarm Optimization (PSO) and Genetic Algorithm (GA), are used too. The genetic algorithm is a technique based on the natural processes of evolution. Survival-of-the-fittest rules are used to select individual design cases out of a population of cases, which become the "parents" of a new population of design cases. As the algorithm evolves through generations (similar to iterations in a typical algorithm), the objective function tends towards an optimum value. Due to the pseudo-random nature of the algorithm and its independency from objective function gradients, it does not become fixed in a local optimum point. First application of GA to pipeline optimization has been introduced by Goldberg and Kuo where they demonstrated its application in a serial liquid pipeline system [10], [11]. Particle Swarm Optimization (PSO) is based on concepts and rules that govern socially organized populations in nature, such as bird flocks, fish schools, and animal herds [8]. The algorithm employs a population of search points that moves stochastically in the search space. Concurrently, the best position ever attained by each individual, also called its experience, is retained in memory. This experience is then communicated to part or the whole population, biasing its movement towards the most promising regions detected so far. The communication scheme is determined by a fixed or adaptive social network that plays a crucial role on the convergence properties of the algorithm [8]. This paper presents application of SQP, GA and PSO methodologies to single-objective optimization and application of GA to multi-objective optimization of four similar units from a compressor station driven by similar gas turbine (N.P MS5002C) as well as four same size coolers.

3. COMPRESSION POWER TRAIN SYSTEM

A four-unit compressor station is considered as an example of a complex power train system. This system Operates on the 2th nationwide gas transfer pipeline between (Farashband – Noorabad), which starts from the site of high pressure gas compressor in Farashband (S1) and runs up to the entrance of the high pressure gas compressor site in Noorabad (S2). Table 1 shows this system consists of four similar compressor units (termed cent0001 to cent0004) driven by four similar gas turbines. Moreover, the station includes four aerial coolers with same size (termed cooler0001 to cooler0004), which are connected in parallel to all of the compressor units. The downstream section of the pipeline is composed of one line with a diameter of 56" and approximately 135.71 km to the next station. Figure 1 shows a schematic of the station and the downstream pipeline section which comprise the power train system as an example for the present optimization exercise.

Table 1: Models of Four Similar Compressor Units and Gas Turbine Drivers

Unit	Compressor Unit	Driver
1	N.P BCL-605	N.P MS5002C
2	N.P BCL-605	N.P MS5002C
3	N.P BCL-605	N.P MS5002C
4	N.P BCL-605	N.P MS5002C

Fig 1: Schematic of the four-Unit Compressor Station and Downstream Pipeline Section under Study.

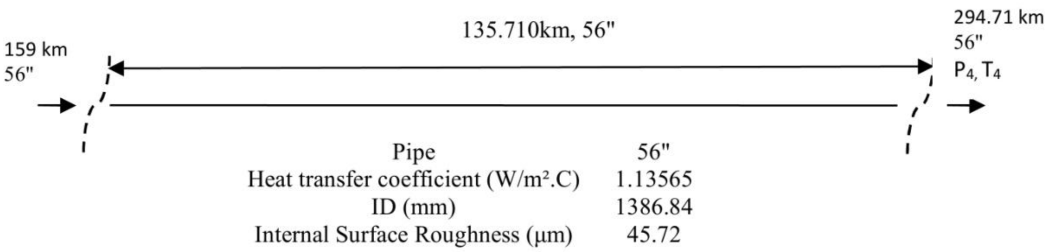

Fig 2: Schematic and Dimensions of the Pipeline Sections Downstream of the Compressor Station.

The downstream section of the pipeline to the next station (135.710 km downstream) is composed of 25 pipes as shown in Figs. 1 and 2. The compressor performance characteristics and associated driver's heat rate map at ambient temperature (90 °F) are shown in Fig. 3.

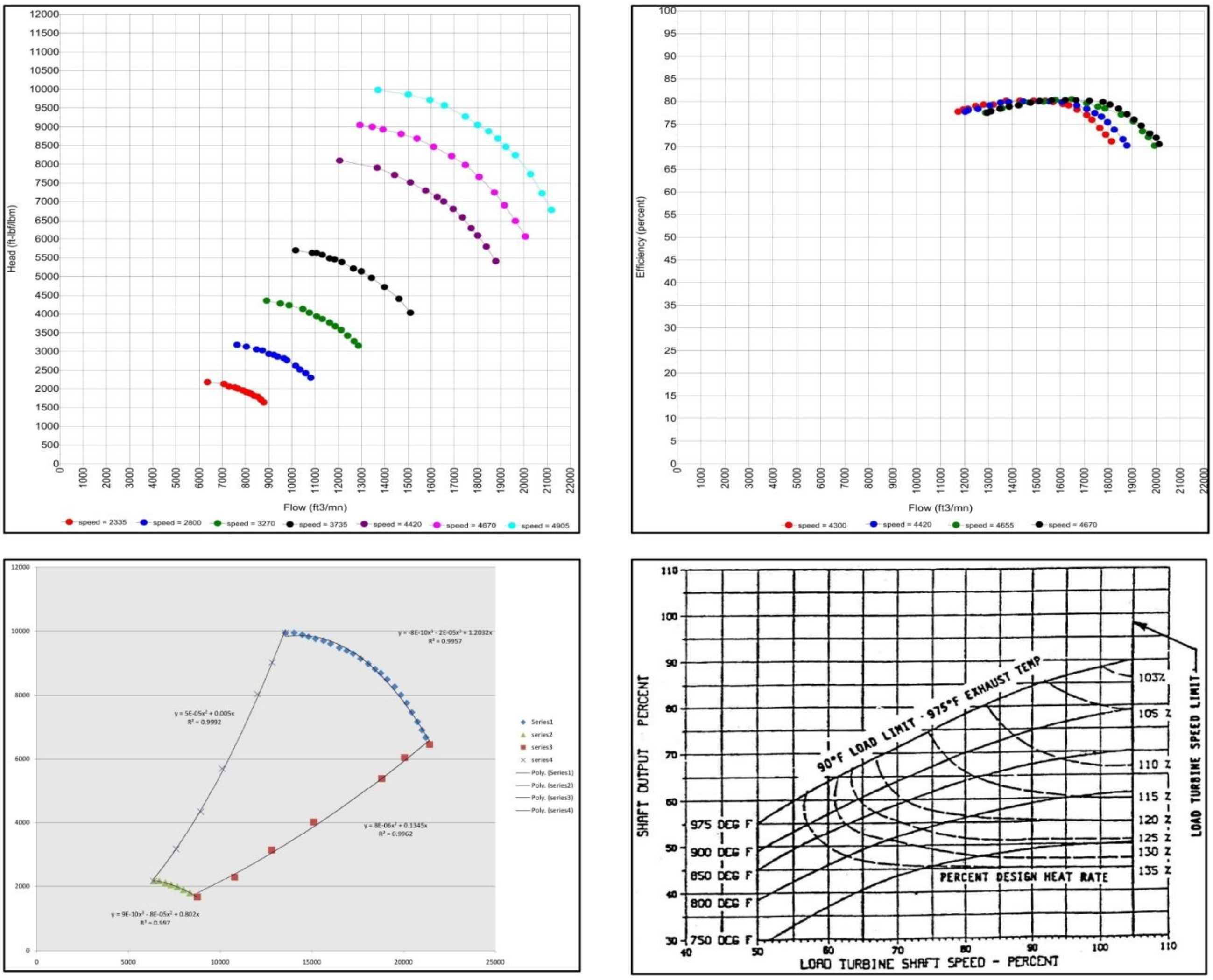

Fig 3: Performance Characteristics of the Compressor and its Gas Turbine Driver at 90°F Ambient Temperature

According to Fig.3, search space is in the range of performance curves and by this keen action so many wrong answers has been discarded. In a single-objective optimization for a given throughput, case-specific input parameters are shown in Table 2. The case study is based on the information of the 2th major gas transmission pipeline of the National Iranian Gas Company, NIGC, or IGAT 2 gas transmission pipeline. A total throughput of 79 MMSCMD of natural gas is transported from Assaluyeh refinery towards the city gate of Noorabad through a NPS 56 gas pipeline. There are significant elevation changes in the pipeline route (see Figure 4).

Table 2: Input Parameters for the Power Train System of Fig. 1.

Input Parameters		
Suction Pressure (P1)	696.2	Psia
Suction Pressure at Next Station (P4)	750	Psia
Suction Temperature (T1)	35.14	°C
Soil Temperature	10	°C
Ambient Temperature	10	°C
Gas Flow	79	MMSCMD

The control variables are:

- Compressor load sharing in terms of the Volume flow split to each compressor unit.
- Downstream Temperature of Coolers.

In this work, because of the continuous nature of the constraints, Constrained Nonlinear Optimization Algorithm - fmincon SQP Algorithm- was used for single-objective optimization and results are compared with two stochastic methods GA and PSO. Table 3 shows the operators of GA and PSO in single-objective optimization as following:

Table 3: Genetic and Particle Swarm Operators

Genetic		Particle Swarm	
population size	20	population size	20
Elitism	2%	C1 (Social Attraction)	1.25
Directional crossover	80%	C2 (Cognitive Attraction)	0.5
Classical crossover	30%	C0 (particle inertia)	0.5

Table 4 gives the selected resolution for each of the control variables above, 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 76 and resulting search space is 7.6E+22. Similar GA data are shown in Table 5 for the case of multi-objective optimizations that include maximizing flow (means that maximizing flow is the other objective in this optimization). The corresponding number of GA strings in this case is 86 and the resulting search space is 7.7E+25.

Table 4: Control Variables in Case of Single-Objective Optimizations with GA.

Control Variable	Min	Max	Resolution	# of Cases	# of String
Compressor Flow Split (MMSCMD) (fraction to Compressor Cent0001)	0.13	0.30	0.001	171	8
Compressor Flow Split (MMSCMD) (fraction to Compressor Cent0002)	0.13	0.30	0.001	171	8
Compressor Flow Split (MMSCMD) (fraction to Compressor Cent0003)	0.13	0.30	0.001	171	8
Compressor Flow Split (MMSCMD) (fraction to Compressor Cent0004)	0.13	0.30	0.001	171	8
Cooler Downstream Temperature (°C) Cooler 0001 case	50	70	0.01	2001	11
Cooler Downstream Temperature (°C) Cooler 0002 case	50	70	0.01	2001	11
Cooler Downstream Temperature (°C) Cooler 0003 case	50	70	0.01	2001	11
Cooler Downstream Temperature (°C) Cooler 0004 case	50	70	0.01	2001	11
Total String Length					76
Design Space					7.6E+22

Table 5: Control Variables in Case of Multi-Objective Optimizations with GA.

Control Variable	Min	Max	Resolution	# of Cases	# of String
Gas Flow (MMSCMD)	40	100	0.1	601	10
Compressor Flow Split (MMSCMD) (fraction to Compressor Cent0001)	0.13	0.30	0.001	171	8
Compressor Flow Split (MMSCMD) (fraction to Compressor Cent0002)	0.13	0.30	0.001	171	8
Compressor Flow Split (MMSCMD) (fraction to Compressor Cent0003)	0.13	0.30	0.001	171	8
Compressor Flow Split (MMSCMD) (fraction to Compressor Cent0004)	0.13	0.30	0.001	171	8
Cooler Downstream Temperature (°C) Cooler 0001 case	50	70	0.01	2001	11
Cooler Downstream Temperature (°C) Cooler 0002 case	50	70	0.01	2001	11
Cooler Downstream Temperature (°C) Cooler 0003 case	50	70	0.01	2001	11
Cooler Downstream Temperature (°C) Cooler 0004 case	50	70	0.01	2001	11
Total String Length					86
Design Space					7.7E+25

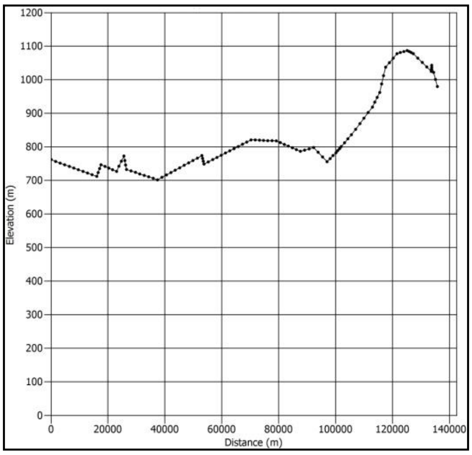

Fig 4: Topology of the Downstream Pipeline Section under Study

A custom-built computer program (Simulator) was used as simulator for modeling of the power train and downstream pipeline section described above. The model simulates the steady-state gas flow from the suction to the compressors to the downstream end of the pipeline section (i.e. to the next compressor station). The model is non-isothermal; it calculates the gas temperature variations across the aerial coolers and along the pipeline section and account for the heat exchange between the pipe and the ground. The pressure drop and temperature profile along the various pipeline sections are obtained from solving:

$$\frac{dP}{dx} = -\frac{16 f\dot{m}^2}{\pi^2 \rho D_i^5} \quad (5)$$

$$\frac{dT}{dx} = -\frac{U\pi D_o}{\dot{m}C_p}(T - T_{soil}) \quad (6)$$

And AGA is used as a flow equation (Eq. 7) [12].

$$\begin{cases} Q = f(\Delta P) \\ Q_b = 0.4696\left(\frac{T_b}{P_b}\right)\left(\frac{P_1^2 - P_2^2}{GT_f Z_{ave} L}\right)^{0.5} .\log\left(3.7\frac{D}{K_e}\right).D^{2.5} \end{cases} \quad (7)$$

Table 6 gives salient specifications of four aerial coolers, and their dimensionless performance characteristics in terms of pressure drop and degree of cooling are given in Figures 5 and 6.

Table 6: Specifications of the Aerial Coolers.

Aerial Cooler	**1 , 2 , 3, 4**
TYPE	Forced Draft
NO. OF PASSES	1
NO. OF BAYS	8
BARE SURFACE AREA/BAY (m^2)	308.8845
NO. 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
NO. OF BUNDLES OF TUBES PER BAY	2
NO. OF TUBES PER BAY	400
TUBE O.D (mm)	25.4
TUBE WALL THICKNESS (mm)	1.65
TUBE I.D (mm)	19.56

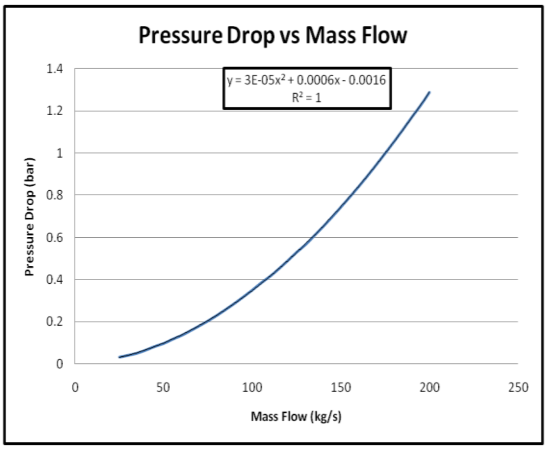

Fig 5: Pressure drop through coolers

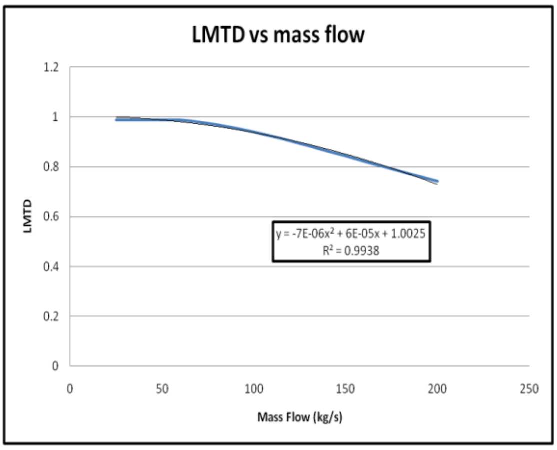

Fig 6: Dimensionless performance characteristics of coolers.

4. RESULTS OF SINGLE-OBJECTIVE OPTIMIZATION

Several single-objective optimization simulations were conducted with GA at different fixed throughput ranging from 40-100 MMSCMD and the results are shown in Fig. 8. A certain throughput of 79 MMSCMD in the mid-range of throughputs was selected for further analysis. Particularly, it is compared with the best (optimum Pareto) case and the worst case on the far right end of the range (see Fig. 8). It should be noted that search space is in the ranges defined in Fig. 3 and this is the reason why the best case and the worst case are close to each other.

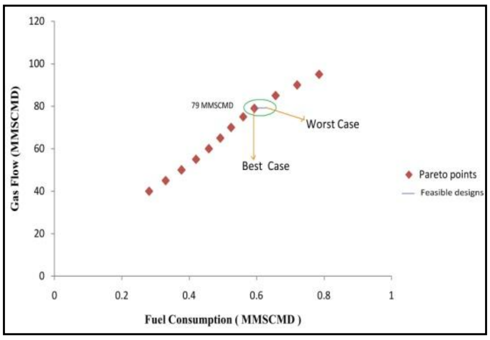

Fig 8: Results of Single-Objective Optimizations at Different Throughputs

Single-objective optimization simulations were conducted at fixed throughout 79 MMSCMD with SQP and the results are shown in Fig. 9, where the resulting total Fuel consumptions are shown on the y-axis, for each of the Iterations shown on the x-axis. This Single-objective optimization also conducted with two stochastic algorithms, GA and PSO, for comparison. The results are shown in Fig. 10 and 11 respectively. Table 7 compares the results of these optimizations and it is obvious that, for stations having the same compressor in parallel, the minimum fuel (energy) consumption is reached when split flows in all compressor units are almost the same. Comparison between two cases (best and worst) is given in more details in Table 8. 0.017 MMSCMD of fuel saving equates to 3% saving in fuel consumption between the best and the worst case for this throughput case.

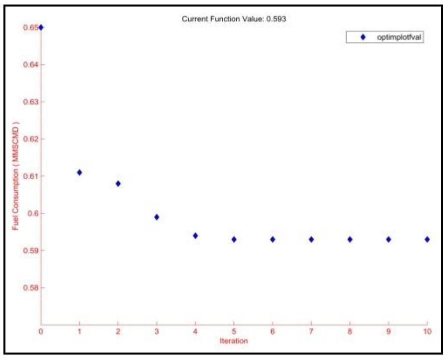

Fig 9: Results of Single-Objective Optimizations with SQP

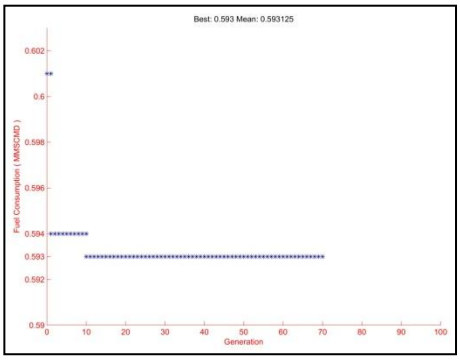

Fig 10: Results of Single-Objective Optimizations with GA

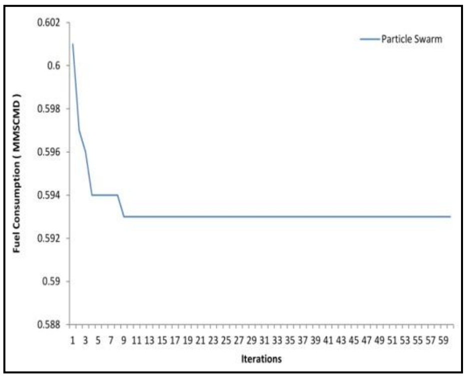

Fig 11: Results of Single-Objective Optimizations with PSO

Table 7: Control Variables in Case of Single-Objective

Results of SQP		Results of GA		Results of PSO	
Downstream Temperature (Cooler 0001)	51 °C	Downstream Temperature (Cooler 0001)	51.36 °C	Downstream Temperature (Cooler 0001)	50 °C
Downstream Temperature (Cooler 0002)	51.6 °C	Downstream Temperature (Cooler 0002)	53.67 °C	Downstream Temperature (Cooler 0002)	50 °C
Downstream Temperature (Cooler 0003)	50 °C	Downstream Temperature (Cooler 0003)	50.58 °C	Downstream Temperature (Cooler 0003)	50 °C
Downstream Temperature (Cooler 0004)	50 °C	Downstream Temperature (Cooler 0004)	53.54 °C	Downstream Temperature (Cooler 0004)	50 °C
Load Sharing (fraction to Compressor Cent0001)	0.25	Load Sharing (fraction to Compressor Cent0001)	0.25	Load Sharing (fraction to Compressor Cent0001)	0.25
Load Sharing (fraction to Compressor Cent0002)	0.25	Load Sharing (fraction to Compressor Cent0002)	0.25	Load Sharing (fraction to Compressor Cent0002)	0.25
Load Sharing (fraction to Compressor Cent0003)	0.25	Load Sharing (fraction to Compressor Cent0003)	0.25	Load Sharing (fraction to Compressor Cent0003)	0.25

Load Sharing (fraction to Compressor Cent0004)	0.25	Load Sharing (fraction to Compressor Cent0004)	0.25	Load Sharing (fraction to Compressor Cent0004)	0.25
Total Fuel Consumption: 0.593485 MMSCMD		Total Fuel Consumption: 0.593082 MMSCMD		Total Fuel Consumption: 0.594509 MMSCMD	

Based on simulations done on this system, cooling plays an efficient role in fuel consumption minimization, but it appears that most of the saving (75%) is derived from optimizing the load sharing among the parallel compressors, only 25% of the saving comes from optimizing the coolers. As mentioned earlier the comparison between the best (optimum Pareto) case and the worst case is shown in Table 8. It appears that potential total fuel consumption saving of up to 3% can be realized from optimum load sharing and optimum downstream temperature of coolers.

Table 8: Comparison between Best and Worst Feasible Case of Transporting 79 MMSCMD of Gas.

	Best case				Worst case				Difference
	1	2	3	4	1	2	3	4	
Flow	19.75	19.75	19.75	19.75	23.621	18.091	18.565	18.723	
Cooler Downstream Temperature (°C)	50	50	50	50	68.6	67.8	67.8	68.6	
Power Required (MW)	15.0043	15.041	15.041	15.041	19.7635	13.9058	14.3651	14.5205	
Head (m)	5299.34	5314.04	5314.04	5314.04	5612.35	5479.91	5491.26	5495.12	
Speed (RPM)	4057.25	4060.48	4060.48	4060.48	4498.33	3966.54	4004.31	4017.28	
Duty of Cooler (MW)	9.06646	9.37668	9.37668	9.37668	2.15003	0.452632	0.559237	0.597117	
Downstream Temperature to next station (T_4)	32.1273 °C				45.3894				
Total Power Required (MW)	60.12				62.56				
Total Duty (MW)	37.1966				3.759				
Total Fuel Consumption (MMSCMD)	0.594				0.6100				0.017

5. RESULTS OF MULTI-OBJECTIVE OPTIMIZATION

In this section, Multi-objective optimization simulations was conducted for minimum total fuel consumption (Minimum Energy) and maximum throughput instead of running the simulation as several single-objective simulations at different throughput. The outcome would be a Pareto front as shown in the results of Fig. 12.

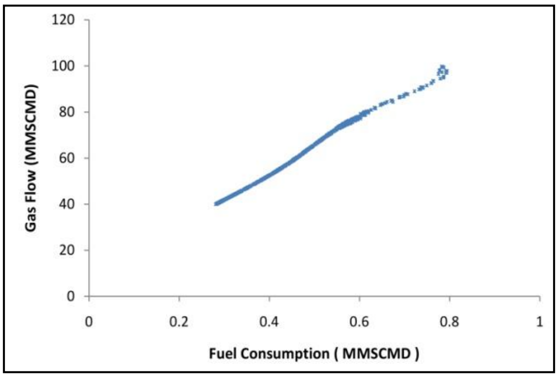

Fig 12: Results of Multi-Objective Optimizations of Throughput and Total Fuel Consumption.

The purpose to do multi-objective optimization is to obtain the optimal operation conditions for minimizing the total fuel consumption and maximizing the throughput. The Pareto front, i.e. the optimum conditions are those represented by the far top left set of points of all of the points shown in the Figure. These points are plotted in Fig. 13 along with the individual single-objective simulations shown in Fig. 8. If both set of simulations are correct, the two sets should lie on top of each other, which is indeed the case as shown in Fig. 13.

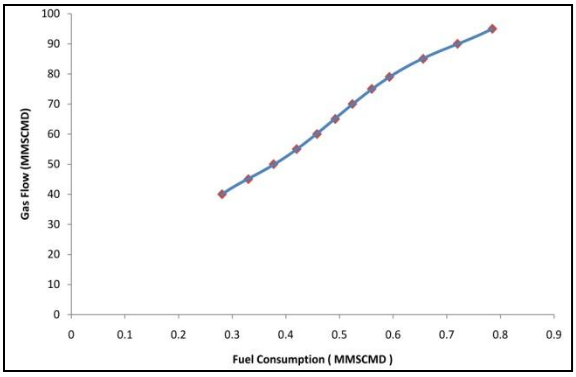

Fig 13: Comparison between Results of Multi-Objective Optimizations vs. Individual Single-Objective Optimizations.

6. CONCLUDING REMARKS

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

1. Single- and multi-objective optimization based on Genetic, Particle Swarm and SQP Algorithms was successfully developed for the entire power train of a multi-unit compressor station involving four similar units, four identical aerial coolers which are connected in parallel to all of the compressor units, and a pipeline section to the downstream station.

2. Single and multi-objective optimization with GA results in 8 and 9 decision variables and an optimization space of 7.6E+22 and 7.7E+25 cases respectively

3. Stations having the same compressor in parallel, the minimum fuel (energy) consumption is reached when split flow in all compressors is the same (Load sharing is equal in all compressors).

4. Based on simulations done on this system, after cooling has an efficient role in fuel consumption minimization but It appears that most of the saving (75%) is derived from optimizing the load sharing among the parallel compressors, while 25% of the saving comes from optimizing the coolers.

5. Based on two cases compared, it appears that a fuel savings of approximately 2-4% could be realized in the field by controlling the compressor flow split ratio and downstream temperature of coolers.

7. NOMENCLATURE

MMSCMD	Million Standard Cubic Meters per Day
BCFD	Billion Cubic Foot per Day
IGAT	Iranian GA Trunk-lines
SQP	Sequential Quadratic Programming
PSO	Particle Swarm Optimization
MNLP	Mixed Non Linear Programming
CP	Specific heat capacity at constant pressure (Btu/lb.F)
Q	Actual inlet flow rate to a compressor unit (MMSCMD)
U	Overall heat transfer coefficient (Btu/h.ft2.F)
Qb	Gas flow rate at base conditions (MMSCMD)
e	Total energy consumption
$\dot{m}$	Mass flow rate
Ps	Suction pressure (psia)
Pd	Discharge pressure (psia)
W	Compressor power (MW)
N	Compressor speed (RPM)
P1	Gas inlet pressure to the pipeline (psia)
D	Inside diameter of the pipeline (in)
H	Adiabatic head across a compressor unit
N.P	NUOVO PIGNONE

8. ACKNOWLEDGMENTS

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