Minimization of Fuel Consumption of Natural Gas Compressor Stations with Similar and Dissimilar Turbo-Compressor Units

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Abstract

This paper studies and compares the results of a simple and fast heuristic method, Genetic Algorithm (GA) and the Exhaustive Search method (ES) concerning the minimization of fuel consumption of a natural gas compressor station (CS). The results, obtained for an input data set (natural gas flow rate of 150 million standard cubic meters per day (MMSCMD), suction pressure of 5.45 MPa and discharge pressure of 6.9 MPa), showed that for a CS with similar TC units, all the applied methods achieved the same solution (fuel consumption rate of 3.620 kg/s). By contrast, for a CS with dissimilar TC units, the GA and ES methods attained a lower fuel consumption rate (3.738 kg/s) compared to that obtained by the heuristic method (3.753 kg/s). The effect of changing the CS flow rate and CS suction and discharge pressures on optimal fuel consumption rate was also investigated. In the first case study, 100 MMSCMD (or 100%) increase in the flow rate, 8.3 bar (or 13%) increase in discharge pressure and 8.3 bar (or 14%) reduction in the suction pressure of the CS caused the optimal fuel consumption rate to increase by 2.41 kg/s (or 99%), 1.02 kg/s (or 33%) and 1.72 kg/s (or 60%), respectively. In the second case study, for the same changes of flow rate and discharge and suction pressures mentioned above, the optimal fuel consumption rate increased by 2.72 kg/s (or 112%), 1.03 kg/s (or 32%) and 1.71 kg/s (or 58%), respectively.

Keywords: Natural gas compressor station; Optimization; Fuel consumption; Genetic Algorithm

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1. Introduction

Natural gas is increasingly used as a source of energy all over the world and the estimations show that its worldwide consumption in 2030 will be twice as much as its present rate (Riva et al. 2006). As natural gas travels through the transmission pipelines, the gas pressure drops due to both the friction with the pipe walls and heat transfer to the surroundings. Therefore there is a need to compensate the pressure by a number of compressor stations (CSs) located along the pipeline.

As an accepted rule of thumb, about 3 to 5% of the transmitted natural gas is consumed for gas turbine drivers to generate power for the compressor stations which amounts to a huge cost because of the large quantities of natural gas transmitted through extensive networks (Borraz-Sanchez and Rios-Mercado 2009; Wu et al. 2000; Carter 1998). Therefore, even a slight improvement in the performance of the gas transportation system can result in great savings.

The nonlinearity of the constraints and objective function, non-convexity of the compressors' operating domain, possibility of on/off state for each turbo-compressor (TC) unit, and the existence of local optima are some features of the CS optimization problem, which make this problem very difficult to be solved using the classical mathematical methods (Borraz-Sanchez and Rios-Mercado 2009; Wu et al. 2000; Chebouba et al. 2009; Rios-Mercado et al. 2006).

The heuristic methods are simple, fast, but unproven optimization tools that have originated from past experiences. The complexity of natural gas system optimization problems highly encourages the use of the heuristic methods (Borraz-Sánchez and Ríos-Mercado 2005). Davidson et al. (2006) applied a heuristic method to minimize the investment cost of a natural gas distribution network. Carter (1996) has described the commonly used heuristic methods for the optimization of fuel consumption in the CSs.

With the ability of setting the control parameters, the evolutionary Genetic Algorithm (GA) is considered as an efficient and powerful optimization tool. Nguyen et al. (2008), and Nguyen and Chan (2006) have given a review of the research works that have used GA method.

The present paper is concerned with the minimization of fuel consumption of CSs. The on/off state for each of the TC units existing in the CS, and also the rate of flow passing through each of the running TC units were considered as the decision variables of the optimization problem. The Pataveh CS with similar TC units located along the third Iranian gas transmission pipeline (IGAT) and the same CS but with the assumption of having dissimilar TC units constitute the case studies of the present paper. A heuristic method based on the same utilization value (Utilization is defined as the ratio of the rate of flow passing through a TC unit to the maximum permissible flow rate) for all running units, and Genetic Algorithm (GA) were applied as the optimization methods and their results and computation times were compared. Furthermore, the results of the heuristic and GA methods were checked through comparison with the results obtained by the Exhaustive Search method (ES). Finally, the impact of changing the values of important input parameters of the studied CS on optimal fuel consumption rate was investigated.

The rest of this paper is organized as follows. The modeling and governing equations of a typical CS are described in section 2. The description of the optimization problem as well as a brief introduction to the optimization methods are presented in section 3. The case studies are introduced in section 4, and the results are presented and discussed in section 5.

2. Modeling and the governing equations

Gas transmission networks are composed of pipelines and CSs as the main components. A schematic diagram of a typical gas network, including a number of CSs and pipelines, is shown in Figure (1). As natural gas travels through the transmission pipelines from a supply point (point

A in Figure (1)) to some delivery points (points B and C in Figure (1)), its pressure drops, mainly due to the friction with pipe walls. This pressure drop should be compensated by a number of CSs located along the pipelines to flow natural gas to the delivery points at required values of pressure and volume flow rate.

A schematic diagram of a CS located between two pipelines, with a number of TC units in parallel, is shown in Figure (2). As shown in Figure (2), each TC unit consists of a natural gas compressor (responsible for compensating the pressure drop), and a gas turbine (also called turbine engine) as the driver of the natural gas compressor. The gas turbine is a double-shaft turbine composed of air compressor, combustion chamber, and low and high pressure (LP, HP) turbines, which will be discussed in detail in section (2.2). The "natural gas compressor" is henceforth shortened to "compressor". The modeling and governing equations of typical CS components are described as follows:

2.1. Natural gas compressor (pipeline compressor)

Equations (1)-(9) show the governing equations of gas flow passing through a typical compressor:

The ratio of compressor isentropic head to the square of rotational speed:

$$\frac{H}{S^2} = b_1 + b_2\left(\frac{Q_{ac}}{S}\right) + b_3\left(\frac{Q_{ac}}{S}\right)^2 \quad (1)$$

The compressor isentropic efficiency:

$$\eta_{c,is} = b_4 + b_5\left(\frac{Q_{ac}}{S}\right) + b_6\left(\frac{Q_{ac}}{S}\right)^2 \quad (2)$$

In equations (1) and (2) as empirical equations proposed by Odom (1990), and Percell and Ryan (1987), b_1 to b_6 are the constant coefficients obtained from the compressor operating map.

The compressor isentropic head in terms of compressor pressure ratio:

$$H = \frac{Z_s R T_s}{\sigma}\left[\left(\frac{p_d}{p_s}\right)^{\sigma} - 1\right] \tag{3}$$

The compressibility factor (Z_s) (Mohring et al. 2004):

$$Z_s = 1 + 0.257\left(p_s / p_c\right) - 0.533\left(p_s / p_c\right)\left(T_c / T_s\right) \tag{4}$$

The compressor discharge temperature after gas compression:

$$T_d = T_s + \frac{T_s}{\eta_{c,is}}\left[\left(\frac{p_d}{p_s}\right)^{\sigma} - 1\right] \tag{5}$$

The compressor power consumption in terms of compressor mechanical efficiency ($\eta_{c,m}$):

$$Power_{shaft} = \frac{H.\dot{m}_d}{\eta_{c,is} \cdot \eta_{c,m}} \tag{6}$$

The required fuel mass flow rate in gas turbine for running the compressor:

$$\dot{m}_f = \frac{Power_{shaft}}{LHV \cdot \eta_{th,gasturbine}} \tag{7}$$

The mass balance in a TC unit (as shown in Figure (2)):

$$\dot{m}_f + \dot{m}_d = \dot{m}_s \tag{8}$$

In the above equations, subscriptions s and d indicate compressor suction and discharge points.

The actual volumetric flow rate passing through a compressor as a function of mass flow rate, pressure and temperature, is obtained from:

$$Q_{ac} = \frac{\dot{m}_d Z_s R T_s}{p_s} \tag{9}$$

2.2. Gas turbine (Driver)

Generally, two-shaft gas turbines are used in gas pipeline applications because of their operational flexibility (Cohen et al. 1987). Part of Figure (2) confined in a dashed box shows a schematic diagram of a two-shaft gas turbine. A gas turbine (including air compressor, combustion chamber, and low and high pressure turbines) provides power to run the air compressor by the high pressure turbine and to run the pipeline compressor by the low pressure turbine (also called power turbine).

The technical specifications of turbine engines are generally associated with their ISO conditions and base load operation. These specifications include maximum power and efficiency ($Power_A$ and $\eta_{th,A}$) and the output shaft's rotational speed (S_A) at which maximum power and efficiency are produced. In most cases though, the turbine operates outside these ISO, base load and optimal conditions; therefore, some corrections are required for estimating the turbine engine's overall performance.

Correction for the ambient temperature

Changes of ambient temperature alter maximum power and efficiency as well as the output shaft's rotational speed at which power and efficiency attain their maximum values (Kurz and Ohanian 2003; Santos 1997). The following equations were used to take these effects into consideration:

$$\frac{Power_A}{Power_B} = f_1\left(\frac{T_{ambient}(K)}{T_{iso}(K)}\right) \qquad (10)$$

$$\frac{\eta_{th,A}}{\eta_{th,B}} = f_2\left(\frac{T_{ambient}(K)}{T_{iso}(K)}\right) \qquad (11)$$

$$\frac{S_B}{S_A} = f_3\left(\frac{T_{ambient}(K)}{T_{iso}(K)}\right) \qquad (12)$$

Correction due to the part load operation

The turbine part load operation decreases the maximum values of power and efficiency, and also decreases the rotational speed at which power and efficiency attain their maximum values (Kurz and Ohanian 2003; Walsh and Fletcher 2004). Equations which consider these effects are:

$$\frac{\eta_{th,C}}{\eta_{th,B}} = f_4\left(\frac{Power_C}{Power_B}\right) \tag{13}$$

$$\frac{S_C}{S_B} = f_5\left(\frac{Power_C}{Power_B}\right) \tag{14}$$

Correction due to the operation out of design rotational speed

For any operating condition of a gas generator (part of the gas turbine which includes air compressor, combustion chamber and HP turbine as was shown in Figure (2)), there is a rotational speed at which the output shaft power and efficiency values are the highest. If the power turbine deviates from this speed, the power and efficiency decrease with the same proportions (Kurz and Ohanian 2003). Equations (15) and (16) were proposed by Kurz and Ohanian (2003), and Kurz and Brun (2009) to take this effect into consideration:

$$\frac{Power_{shaft}}{Power_C} = 2\left(\frac{S}{S_C}\right) - \left(\frac{S}{S_C}\right)^2 \tag{15}$$

$$\frac{\eta_{th,gas\,turbine}}{\eta_{th,C}} = \frac{Power_{shaft}}{Power_C} \tag{16}$$

Where, $Power_{shaft}$ and S represent the power and rotational speed required by the pipeline compressor, respectively.

The set of nonlinear equations, including Equations (1)-(16) for each TC unit, was solved using Newton-Raphson method in this paper. Newton-Raphson method is a widely used method for solving a set of nonlinear equations which has the advantage of converging quadratically (Gerald and Wheatley 1999).

3. Optimization

For the specified rate of flow passing through the CS, and the specified suction and discharge pressures of the CS, the optimization problem in this paper is supposed to determine the on/off state for each TC unit in the CS and the rate of flow allocated to each of the active units, so that the fuel consumption rate of the CS is minimized.

The optimization problem is mathematically expressed by Equation (17) (Carter 1996), where n is the number of TC units existing in the CS, J_i is an integer variable with the value of 1/0 for the on/off state of unit i, and Q_i is the volume flow rate of natural gas that enters unit i.

$$Minimize\left[\ \sum_{i=1}^{n} J_i \cdot \dot{m}_{f_i}(Q_i)\right] \quad ; J_i \in \{0,1\} \tag{17}$$

$$\text{Constraints} \begin{cases} \sum_{i=1}^{n} J_i Q_i = Q_{station} \\ if \quad J_i = 1 \rightarrow Q_{i,min} \le Q_i \le Q_{i,max} \end{cases}$$

The first constraint in Equation (17) states that the sum of the input flow rates of the running units must be equal to the inlet flow rate ($Q_{station}$) of the CS. The second constraint is related to the feasible operating domain of each unit, and states that the amount of flow which enters each running unit must be between certain minimum and maximum values.

The feasible operating domain of a typical compressor (bounded by maximum and minimum speed, surge and stonewall lines) as well as the compressor minimum and maximum permissible volume flow rates for an arbitrary isentropic head are shown in Figure (3).

The optimization methods applied in this paper (which their codes were developed by the authors at the Energy Systems Improvement Laboratory (ESIL)) are briefly described as follows:

Heuristic optimization method based on equal utilization

The heuristic method applied in the present paper for the minimization of the CS fuel consumption rate is based on the assumption of the same utilization value for all running TC units (Carter 1996). This method is henceforth shortened to the "heuristic method". Utilization is defined as the ratio of the rate of flow passing through a TC unit to the maximum permissible flow rate through that TC unit ($\alpha = Q_i / Q_{i,max}$). It should be noted that equal utilization values implies equal flow rates for similar units (since similar units have identical maximum permissible flow rates), however, this notion doesn’t hold true for dissimilar units.

Figure (4) schematically shows the flow chart of steps to be followed to obtain the fuel consumption rate based on the heuristic method, for a specified combination of on/off states of the units (i.e., for a specified J). These steps are followed for each possible combination; and the combination with the minimum fuel consumption rate is selected as the optimal solution.

Genetic optimization Algorithm (GA)

Evolutionary algorithms are random search methods that mimic the natural evolution. These algorithms start with a population of possible solutions and repeatedly generate a new population from the last one based on the survival of fitter solutions, with the hope of finding solutions with better objective functions. The flow chart of GA steps (as an evolutionary algorithm) is shown in Figure (5). These steps are also briefly described below (Gen and Cheng 2000; El-Mahdy et al. 2010; Hu and Fang 2012):

Formation of the first population

The formation of the first population (generation) is the first step in GA procedure. A population consists of a number of chromosomes (individuals), each a string of coded bits (genes), which represents a single solution of the problem under study. The first population is created by randomly choosing the binary value of 0 or 1 for each bit.

Selection process and the mating pool

The next step is to select some individuals to produce the offspring (children) and establish the new generation. In the selection process, individuals with better objective functions have a greater chance of being selected. A collection of selected individuals makes up the mating pool.

Crossover and mutation

After parents are randomly chosen from the selected individuals in the mating pool, they undergo the crossover procedure in order to produce offspring. Crossover produces offspring that inherit their genes from both parents. Then, mutation is applied on the children, which alters the initial values of some of their genes. Mutation makes it possible for the children to have some different gene values than their parents.

Elitism

Elitism is a method which copies the best chromosome (or a few best chromosomes) of every generation to the next generation without any change.

The Roulette-Wheel selection, single point crossover, and the uniform mutation were the GA operators used in this paper. Furthermore, the best chromosome of every generation was copied to the next generation without any change. Values of 80%, 5% and 100 were chosen for crossover rate, mutation rate and population size, respectively. Unchanged best solution for a sequence of 50 consecutive generations was considered as the convergence criterion for the GA.

Exhaustive Search method (ES)

ES method computes the objective functions for all possible solutions, and selects the solution with the best objective function as the optimal solution. Since ES method certainly reaches the global optimal solution, it will be the preferred method of optimization if it can solve the problem under study within a desired run time. However, except for simple cases (cases which do not include many kinds and numbers of TC units, such as one studied in this paper), and when the step size for continuous decision variables (i.e. volume flow rate in the problem studied in this paper) is coarse, ES method requires unreasonable computing time. It should be noted that ES method has been applied here just as a guide for checking the accuracy of heuristic and GA optimization results.

4. Case studies

Two case studies were investigated in the present paper.

The Pataveh CS with six parallel A-type TC units, located along the third Iranian gas transmission pipeline at a distance of 423 km from the starting point, was considered in the first case study.

In the second case study, the Pataveh CS was assumed with three A-type and three B-type TC units (total of six units).

The constant coefficients of A-type and B-type compressors are shown in Table (1). Parts of the input data which were the same for both case studies have been listed in Table (2).

Constant coefficients of four second-order polynomial equations $\left(a_1 x^2 + a_2 x + a_3\right)$, which were obtained (by curve fitting) for the functions $f_1 \, to \, f_3$ and f_5 in Equations (10)-(12) and (14), are shown in Table (3). Also, a logarithmic function was obtained for f_4 ($f_4 = 0.2457 \, \mathrm{Ln}\left(x\right)$ + 1). It is worth mentioning that the above functions have been verified by Sanaye and Mahmoudimehr (2012a).

5. Discussion and Results

5.1. Results of the first case study (CS with similar TC units)

In the first case study, both the GA and heuristic methods achieved the same solution, which was also verified by the ES method. The optimum values of decision variables, obtained by the optimization procedures, were shown in Table (4). Furthermore, some of computed operating parameters at the optimum point as well as optimum value of the objective function (total fuel consumption rate) were listed in Table (5). Tables (4) and (5) indicate that four out of six TC units in a CS should operate identically (i.e., with equal values of flow rate, utilization, speed, required power, etc.) in order to achieve the optimal solution. This finding indicated that the assumption of ‘same utilization’ that was used by the heuristic method for all the running TC units led to optimal solution and that the GA or ES method could not achieve a better solution.

The flow rate and suction and discharge pressures are some of the operating parameters that significantly affect the fuel consumption rate of a CS. To study the effect of each of the aforementioned parameters on the optimal fuel consumption rate, the values of all the other parameters in the input data were kept constant (at the values listed in Tables 1-3) and the optimal fuel consumption rate was computed for different values of the investigated parameter.

Figs. 6-8 show the changes of optimal fuel consumption rate with CS flow rate, suction pressure and discharge pressure, respectively. According to these figures, an increase in the flow rate or discharge pressure of the CS or a reduction in its suction pressure led to an increase in the optimal fuel consumption rate. This outcome was due to the fact that each of the aforementioned changes increased the required power consumption of the CS according to Equations (3) and (6). As is illustrated in Figs. 6-8, with the variations of CS flow rate, suction pressure and discharge pressure from 100 to 200 MMSCMD, 5.03 to 5.86 MPa and 6.48 to 7.31 MPa, respectively, the optimal fuel consumption rate correspondingly varied from 2.430 to 4.836 kg/s, 4.587 to 2.869 kg/s and 3.099 to 4.115 kg/s.

5.2. Results of the second case study (CS with dissimilar TC units)

The optimization results obtained by the heuristic, GA and ES methods are presented and compared in Tables (6) and (7). As is shown in these Tables, all the applied methods predicted the same number of A- and B-type active units (three A-type units and one B-type unit). However, GA attained a lower fuel consumption rate (3.738 kg/s) compared to that obtained by the heuristic method (3.753 kg/s). It should be noted that the ES results confirmed the validity of GA results. The reason for the discrepancy in fuel consumption rates obtained by the heuristic and GA methods is that, in contrast to the heuristic method which obtained the same utilization value (91.4%) for all the running units, the GA method predicted different values of utilization for dissimilar units (95% for A-type units and 75.7% for B-type units). This finding indicates that although the assumption made by the heuristic method (equal utilization values for all the running units) was accurate for the CS with similar units, it did not lead to optimal solution for the CS with dissimilar units.

The effects of the CS operating parameters on optimal fuel consumption rate were also investigated for the second case study. As is illustrated in Figs. 6-8, in the second case study, with the variations of CS flow rate, suction pressure and discharge pressure from 100 to 200 MMSCMD, 5.03 to 5.86 MPa and 6.48 to 7.31 MPa, respectively, the optimal fuel consumption rate correspondingly varied from 2.430 to 5.152 kg/s, 4.690 to 2.978 kg/s and 3.225to 4.251 kg/s. The average run times of heuristic, GA and ES methods on an Intel (R) Core (TM) i5 2.53 GHz processor were about 0.02, 34.6 and 274.8 seconds, respectively.

6. Conclusions

The minimization of fuel consumption by natural gas compressor stations (CSs) was studied in this paper. A heuristic method (assuming the same utilization value for all the running turbo-compressor (TC) units), the Genetic Algorithm (GA) and the Exhaustive Search method (ES) were employed as optimization methods.

For the CS with similar TC units, the optimization methods applied in this paper achieved the same solution (a fuel consumption rate of 3.620 kg/s). In this case, the simple and fast heuristic method achieved a global optimal solution, and it was unnecessary to use other methods with higher degrees of complexity and longer computation times.

By contrast, for the CS with dissimilar units, the assumption made by the heuristic method (equal utilizations for all the running units regardless of their type) did not lead to optimal solution. In this case, by considering different utilization values for dissimilar TC units (95% for A-type units and 75.7% for B-type units), the GA method could attain a lower fuel consumption rate (3.738 kg/s) compared to that obtained by the heuristic method (3.753 kg/s). The mentioned heuristic method assumed the same utilization value of 91.4% for all the running units.

Finally, it was observed that an increase in CS flow rate and discharge pressure and a reduction in CS suction pressure results in an increase in the optimal fuel consumption rate.

Abbreviations

CS = Compressor station

ES = Exhaustive search method

MMSCMD = Million standard cubic meters per day

TC = Turbo-compressor

Notation

b_1 *to* b_6 = Constant values for modeling a compressor

f_1 *to* f_6 = Functions considered for modeling a two-shaft gas turbine

H = Isentropic head (MJ/kg)

J_i = An integer variable with the value of 1/0 for the on/off state of unit i

LHV = Lower heating value of natural gas (MJ/kg)

$\dot{m}_d$ = Mass flow rate of natural gas passing through the compressor $(\mathrm{kg/s})$

$\dot{m}_f$ = Mass flow rate of fuel (natural gas) consumed by the gas turbine engine $(\mathrm{kg/s})$

$\dot{m}_s = \dot{m}_f + \dot{m}_d$ = Mass flow rate of natural gas for one turbo-compressor unit $(\mathrm{kg/s})$

p_c = Natural gas critical pressure (MPa)

p_d = Discharge pressure $(\mathrm{M\,Pa})$

p_s = Suction pressure $(\mathrm{M\,Pa})$

$Power_A$ = Gas turbine maximum power output under ISO conditions and the base load operation (MW)

$Power_B$ = Gas turbine maximum power output at a typical ambient temperature and the base load operation (MW)

$Power_C$ = Gas turbine maximum power output at a typical ambient temperature and a part load operation (MW)

$Power_{shaft}$ = Compressor power consumption (MW)

Q_{ac} = Actual volumetric flow rate of natural gas passing through a compressor (m^3/s)

Q_i = Actual volumetric flow rate of natural gas that enters unit i (m^3/s)

$Q_{i,max}$ = Maximum permissible flow rate of natural gas that enters unit i (m^3/s)

$Q_{i,min}$ = Minimum permissible flow rate of natural gas that enters unit i (m^3/s)

$Q_{station}$ = CS actual volumetric flow rate (m^3/s)

R = Gas constant ($\mathrm{MJ/kg.K}$)

S = Rotational speed (rpm)

S_A = Rotational speed at which maximum power and efficiency are produced under ISO conditions and the base load operation (rpm)

S_B = Rotational speed at which maximum power and efficiency are produced under a typical ambient temperature and the base load operation (rpm)

S_C = Rotational speed at which maximum power and efficiency are produced under a typical ambient temperature and a part load operation, (rpm)

$T_{ambinet}$ = Ambient temperature (K)

T_c = Natural gas critical temperature (K)

T_d = Discharge temperature (K)

T_{iso} = Temperature at ISO conditions (K)

T_s = Suction temperature (K)

Z_s = Compressibility factor at the suction side

α = Utilization

$\eta_{c,is}$ = Compressor isentropic efficiency

$\eta_{c,m}$ = Compressor mechanical efficiency

$\eta_{th,A}$ = Gas turbine maximum thermal efficiency under ISO conditions and the base load operation

$\eta_{th,B}$ = Gas turbine maximum thermal efficiency at a typical ambient temperature and the base load operation

$\eta_{th,C}$ = Gas turbine maximum thermal efficiency at a typical ambient temperature and a part load operation

$\eta_{th,gasturbine}$ = Gas turbine thermal efficiency

σ = Isentropic exponent

References

Borraz-Sánchez, C. and Ríos-Mercado, R.Z. (2005). ” Hybrid metaheuristics.” *A hybrid meta-heuristic approach for natural gas pipeline network optimization*, M. J. Blesa, C. Blum, A. Roli, and M. Sampels, eds.,Springer, Berlin, Germany, 54-65.

Borraz-Sánchez, C., and Ríos-Mercado, R.Z. (2009). “Improving the operation of pipeline systems on cyclic structures by tabu search.”. *Comput. Chem. Eng.*, 33(1), 58-64.

Carter, R.G. (1996). “Compressor station optimization: computational accuracy and speed.” *28th Annual Meeting Pipeline Simulation Interest Group (PSIG)*, San Francisco, California, USA, (23-25 Oct).

Carter, R.G. (1998). “Pipeline Optimization: Dynamic Programming after 30 Years.” *30th Annual Meeting Pipeline Simulation Interest Group (PSIG)*, Denver, Colorado, USA, (28-30 Oct).

Chebouba, A., Yalaoui, F., Smati, A., Amodeo, L., Younsi, K., and Tairi, A. (2009). “Optimization of natural gas pipeline transportation using ant colony optimization.” *Comput. Oper. Res.*, 36(6), 1916-1923.

Cohen, H., Rogers, G.F.C., and Saravanamuttoo, H.I.H. (1987) “Gas Turbine Theory.” Longman Publication Group, London, 336-369.

Davidson, R.A., Lembo, A.J., Ma, J., Nozick, L.K., and O’Rourke, T.D. (2006). “Optimization of investments in natural gas distribution networks.” *J. Energy Eng.*, 132 (2), 52-60.

El-Mahdy, O.F.M., Ahmed, M.E.H., and Metwalli, S. (2010). “Computer aided optimization of natural gas pipe networks using genetic algorithm.” *Appl. Soft Comput.*, 10(4), 1141-1150.

Gen, M., and Cheng, R. (2000). “*Genetic algorithms and engineering optimization*.” John Wiley & Sons, New York.

Gerald, C.F., and Wheatley, P.O., (1999) “*Applied numerical analysis*.” Addison Wesley Longman Inc, Boston, 174-178.

Hu, W., and Fang, Y. (2012). “Multi-model parameters identification for main steam temperature of ultra-supercritical units using improved genetic algorithm.” *J. Energy Eng*., in press.

Kurz, R., and Brun, K. (2009). “Degradation of gas turbine performance in natural gas service.” *J. Nat. Gas Sci. Eng*., 1(3), 95-102.

Kurz, R., and Ohanian, S. (2003). “Modeling turbomachinery in pipeline simulations.” *35th Annual Meeting Pipeline Simulation Interest Group (PSIG)*, Bern, Switzerland, (15-17 Oct).

Mohring, J., Hoffmann, J., Halfmann, T., Zemitis, A., and Basso, G. (2004). “Automated model reduction of complex gas pipeline networks”. *36th Annual Meeting Pipeline Simulation Interest Group (PSIG)*, Palm Springs, California, USA, (20-22 Oct).

Nguyen, H.H., and Chan, C.W. (2006). “Applications of artificial intelligence for optimization of compressor scheduling.” *Eng. Appl. Artif. Intel*., 19(2), 113-126.

Nguyen, H.H., Uraikul, V., Chan, C.W., and Tontiwachwuthikul, P. (2008). “A comparison of automation techniques for optimization of compressor scheduling.” *Adv. Eng. Softw*., 39(3), 178-188.

Odom, F.M. (1990). “Tutorial on modeling of gas turbine driven centrifugal compressors.” *22nd Annual Meeting Pipeline Simulation Interest Group (PSIG)*, Baltimore, Maryland, USA (18-19 Oct).

Percell, P.B., and Ryan, M. J. (1987). “Steady-state optimization of gas pipeline network operation.” *19th Annual Meeting Pipeline Simulation Interest Group (PSIG)*, Tulsa, Oklahoma, USA, (22-23 Oct).

Rios-Mercado, R.Z., Kim, S., and Boyd, E.A. (2006). “Efficient operation of natural gas transmission systems: a network-based heuristic for cyclic structures.” *Comput. Oper. Res.*, 33(8), 2323-2351.

Riva, A., Angelosante, S.D., and Trebeschi, C. (2006). “Natural gas and the environmental results of lifecycle assessment.” *Energy*., 31(1), 138-148.

Sanaye, S., and Mahmoudimehr, J. (2012a). “Technical assessment of isothermal and non-isothermal modelings of natural gas pipeline operational conditions.” *Oil Gas Sci. Technol.*, 67(3), 435-449.

Sanaye, S., and Mahmoudimehr, J. (2012b). “Minimization of fuel consumption in cyclic and non-cyclic natural gas transmission networks: assessment of genetic algorithm optimization method as an alternative to non-sequential dynamic programming.” *J. Taiwan Inst. Chem. Eng*., 43(6), 904-917.

Santos, S.P.D. (1997). “Transient analysis a must in gas pipeline design.” *29th Annual Meeting Pipeline Simulation Interest Group (PSIG)*, Tucson ,Arizona, USA, (15-17 Oct).

Walsh, P. P., and Fletcher, P. (2004). “*Gas turbine performance*.” Blackwell Science Ltd, Oxford, UK, 383-443.

Wu, S., Rios-Mercado, R.Z., Boyd, E.A., and Scott, L. R. (2000). “Model relaxations for the fuel cost minimization of steady-state gas pipeline networks.” *Math. Comput. Model.* , 31 (2-3) , 197-220.

Table captions:

Table 1. Constant coefficients for the A- and B-type compressors

Table 2. Input data for both case studies

Table 3. Constant coefficients of the functions f_1 *to* f_3 and f_5 in Equations (10)-(12) and (14)

Table 4. Optimum value of decision variables obtained by the heuristic, GA and ES methods in the first case study

Table 5. Computed operating parameters at the optimum point obtained by the heuristic, GA and ES methods in the first case study

Table 6. Optimum value of decision variables obtained by each of the heuristic, GA and ES methods in the second case study

Table 7. Computed operating parameters at the optimum point obtained by each of the heuristic, GA and ES methods in the second case study

Table 1. Constant coefficients of the A- and B-type compressors

	A-type compressor	B-type compressor
b_1	4.8089×10^{-4}	8.294×10^{-4}
b_2	1.2287	1.897
b_3	-1.1086×10^{3}	-2.532×10^{3}
b_4	-1.4005	13.929
b_5	2.1932×10^{5}	2.54×10^{5}
b_6	-1.4016×10^{8}	-2.289×10^{8}
$(Q/S)_{min}\left(\frac{m^3/s}{rev/min}\right)$	6.15×10^{-4}	3.76×10^{-4}
$(Q/S)_{\max}\left(\frac{m^3/s}{rev/min}\right)$	11.78×10^{-4}	8.53×10^{-4}

Table 2. Input data for both case studies

Rate of flow passing through the CS (MMSCMD)	150
Suction pressure (p_s) (MPa)	5.45
Discharge pressure (p_d) (MPa)	6.89
Suction temperature (T_s) (K)	288.15
Ambient temperature ($T_{ambient}$) (K)	288.15
Maximum allowable driver speed (S_{max}) (rpm)	7700
Minimum allowable driver speed (S_{min}) (rpm)	4500
Turbine output power at the design point ((MW)	25.4
Turbine efficiency at the design point (%)	35.1
Turbine speed at the design point (rpm)	7350

Table 3. Constant coefficients of the functions $f_1\ to\ f_3$ and f_5 in Equations (10)-(12) and (14)

function	a_1	a_2	a_3
f_1	-4.3115	6.6618	-1.3618
f_2	-2.4918	4.4951	-1.0074
f_3	-0.4275	0.6710	0.7566
f_5	-0.397	1.0165	0.3777

Table 4. Optimum value of decision variables obtained by the heuristic, GA and ES methods in the first case study

	Optimum on/off state	Optimum TC flow rate (MMSCMD)
TC unit1	On	37.5
TC unit2	On	37.5
TC unit3	On	37.5
TC unit4	On	37.5
TC unit5	Off	0
TC unit6	Off	0

Table 5. Computed operating parameters at the optimum point obtained by the heuristic, GA and ES methods in the first case study

	Utilization (%)	Compressor speed (rpm)	Compressor required power (MW)	Fuel consumption rate (kg/s)
TC unit1	84.4	7035	12.5	0.905
TC unit2	84.4	7035	12.5	0.905
TC unit3	84.4	7035	12.5	0.905
TC unit4	84.4	7035	12.5	0.905
TC unit5	0	0	0	0
TC unit6	0	0	0	0
Total fuel consumption rate (kg/s)				3.620

Table 6. Optimum value of decision variables obtained by each of the heuristic, GA and ES methods in the second case study

	Heuristic method		GA and ES methods	
	Optimum on/off state	Optimum TC flow rate (MMSCMD)	Optimum on/off state	Optimum TC flow rate (MMSCMD)
TC unit 1 (A-type)	On	40.6	On	42.2
TC unit 2 (A-type)	On	40.6	On	42.2
TC unit 3 (A-type)	On	40.6	On	42.2
TC unit 4 (B-type)	On	28.2	On	23.4
TC unit 5 (B-type)	Off	0	Off	0
TC unit 6 (B-type)	Off	0	Off	0

Table 7. Computed operating parameters at the optimum point obtained by each of the heuristic, GA and ES methods in the second case study

	Heuristic method				GA and ES methods			
	Utilization (%)	Speed (rpm)	Compressor Power (MW)	Fuel consumption rate (kg/s)	Utilization (%)	Speed (rpm)	Compressor Power (MW)	Fuel consumption rate (kg/s)
TC unit 1 (A-type)	91.4	7316	14.1	0.982	95.0	7469	15	1.026
TC unit 2 (A-type)	91.4	7316	14.1	0.982	95.0	7469	15	1.026
TC unit 3 (A-type)	91.4	7316	14.1	0.982	95.0	7469	15	1.026
TC unit 4 (B-type)	91.4	6542	10.6	0.806	75.7	5930	8	0.66
TC unit 5 (B-type)	0	0	0	0	0	0	0	0
TC unit 6 (B-type)	0	0	0	0	0	0	0	0
Total fuel consumption rate (kg/s)				**3.753**	Total fuel consumption rate (kg/s)			**3.738**

Figure captions:

Fig.1. Schematic diagram of a typical natural gas transmission network

Fig.2. Schematic diagram of a typical natural gas compressor station

Fig.3. Feasible operating domain of a typical compressor

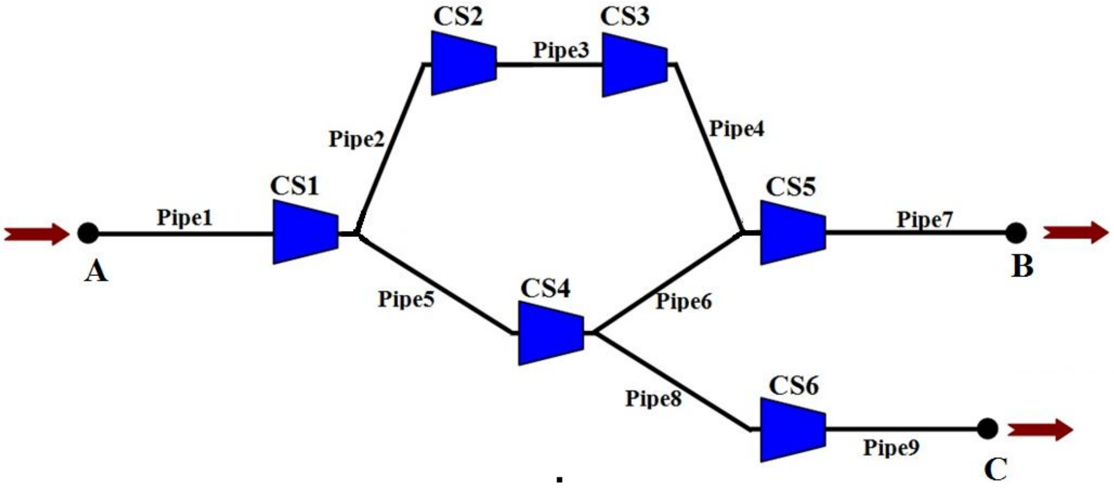
Fig.4. Flow chart of the heuristic method

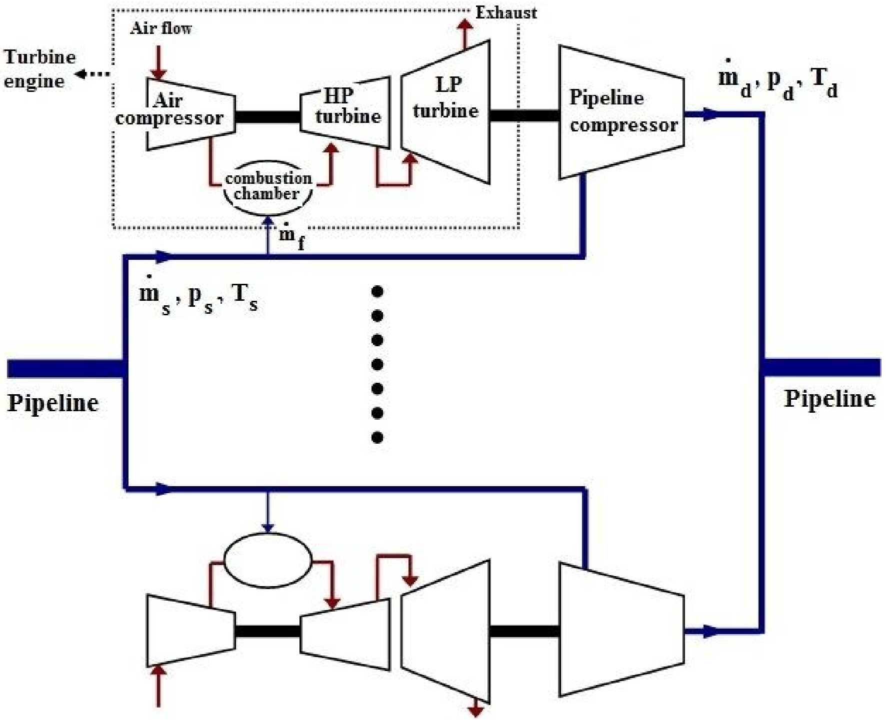
Fig.5 Flow chart of GA

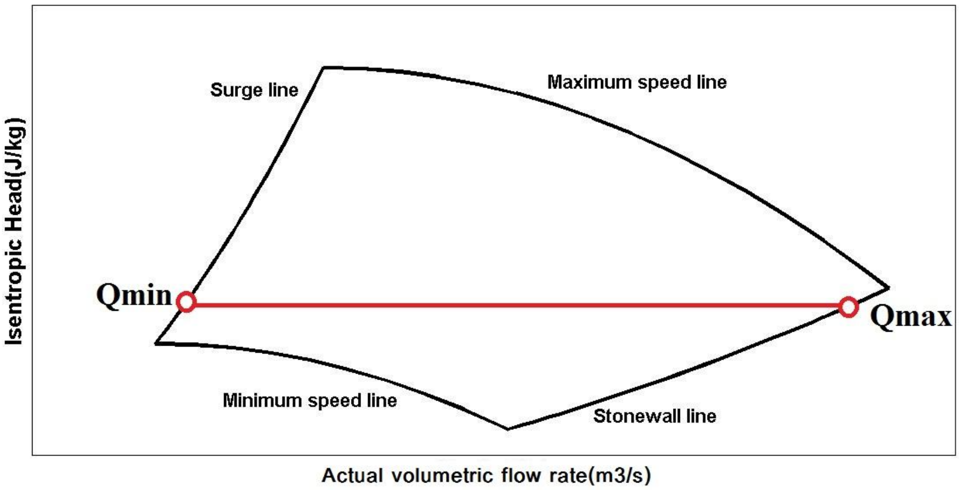
Fig.6. Optimal value of fuel consumption mass flow rate as a function of compressor station volume flow rate

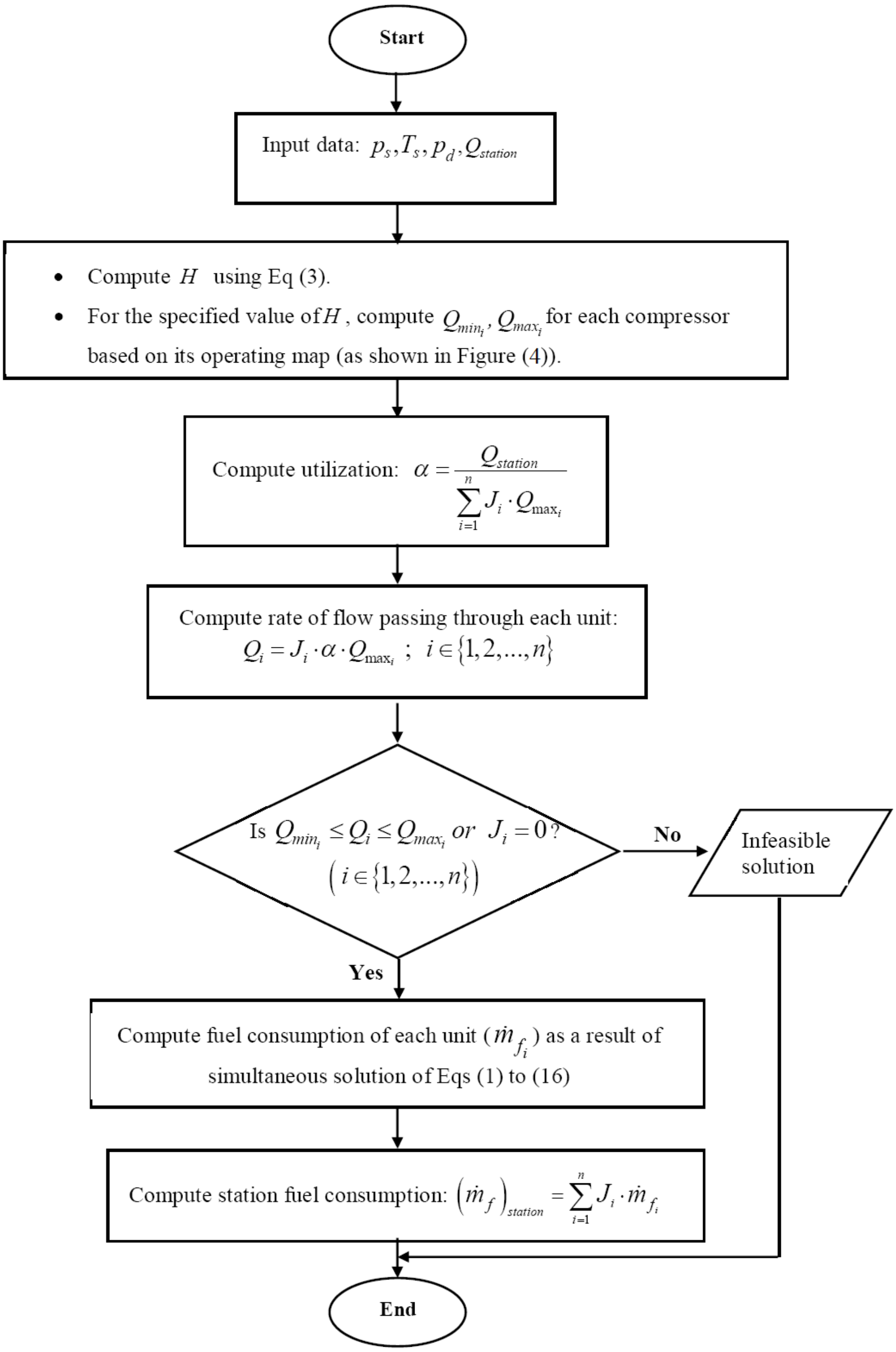
Fig.7. Optimal value of fuel consumption mass flow rate as a function of compressor station suction pressure

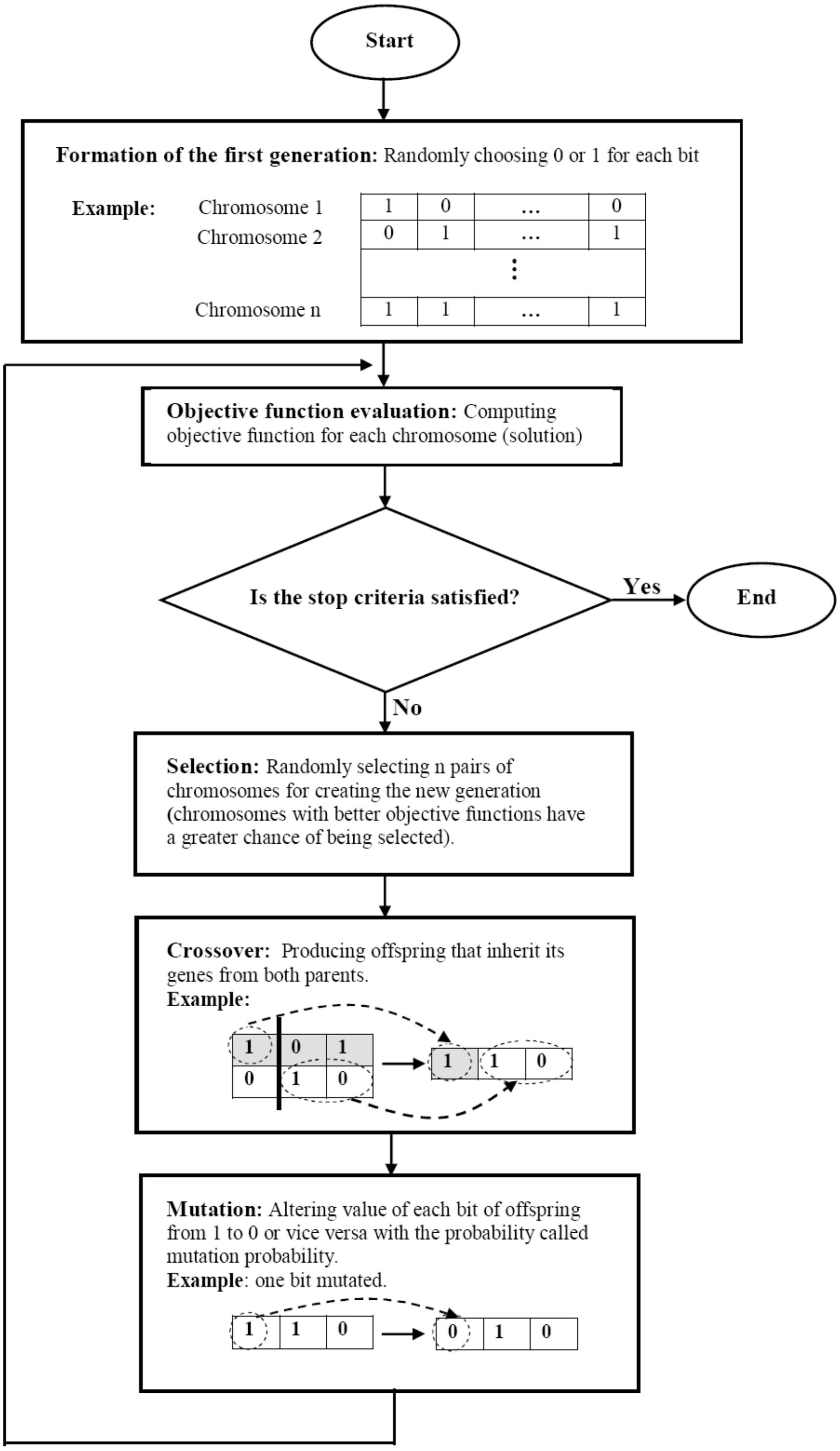
Fig.8. Optimal value of fuel consumption mass flow rate as a function of compressor station discharge pressure

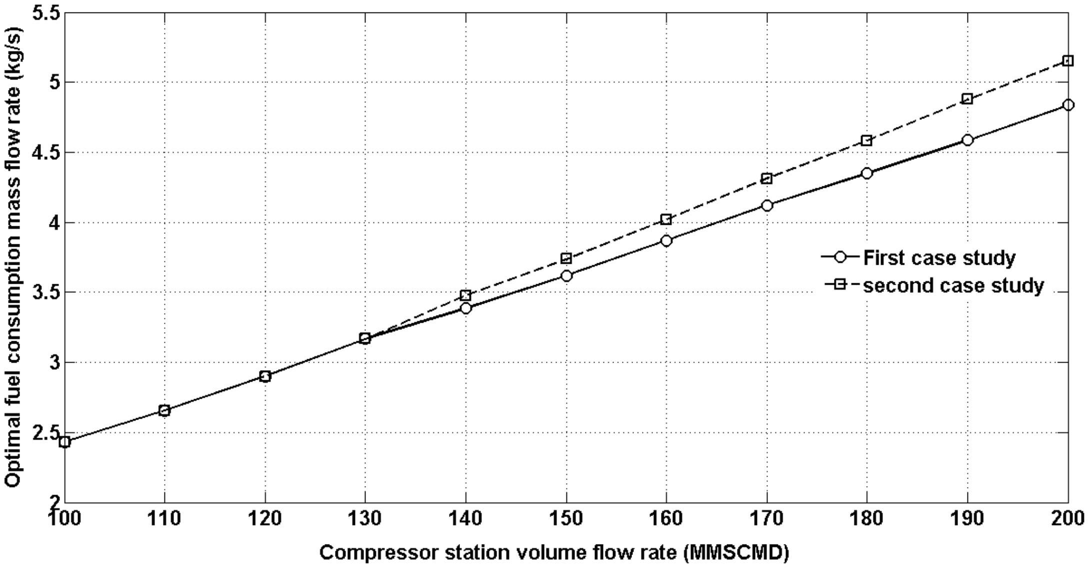

CS2
CS3
Pipe3
Pipe2
Pipe4
CS1
CS5
Pipe1
Pipe7
A
B
Pipe5
CS4
Pipe6
CS6
Pipe8
Pipe9
C

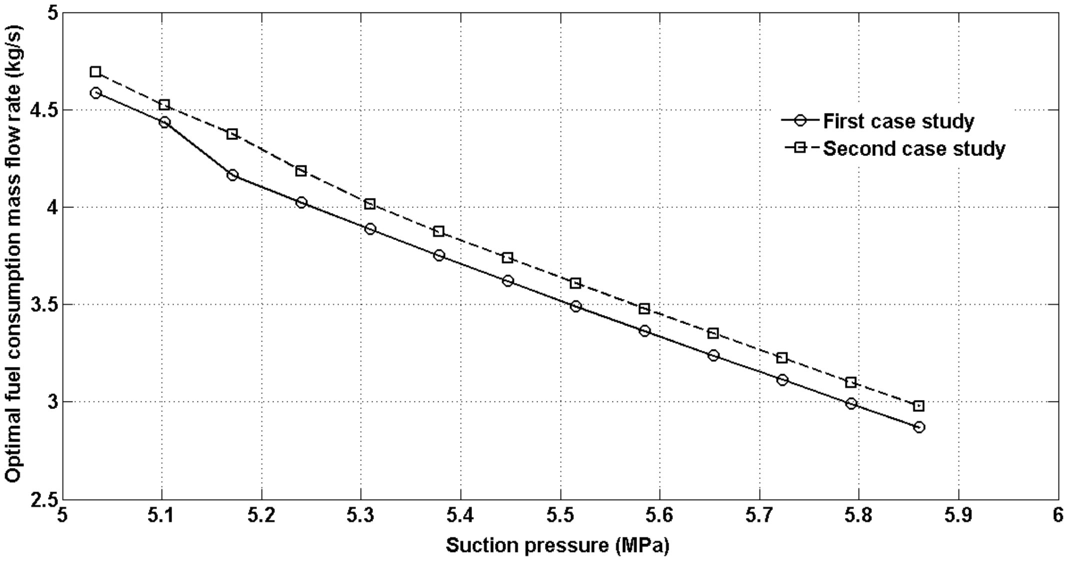

Exhaust
Air flow
Turbine engine
Air compressor
HP turbine
LP turbine
Pipeline compressor
$\dot{m}_d, p_d, T_d$
combustion chamber
$\dot{m}_f$
$\dot{m}_s, p_s, T_s$
Pipeline
Pipeline

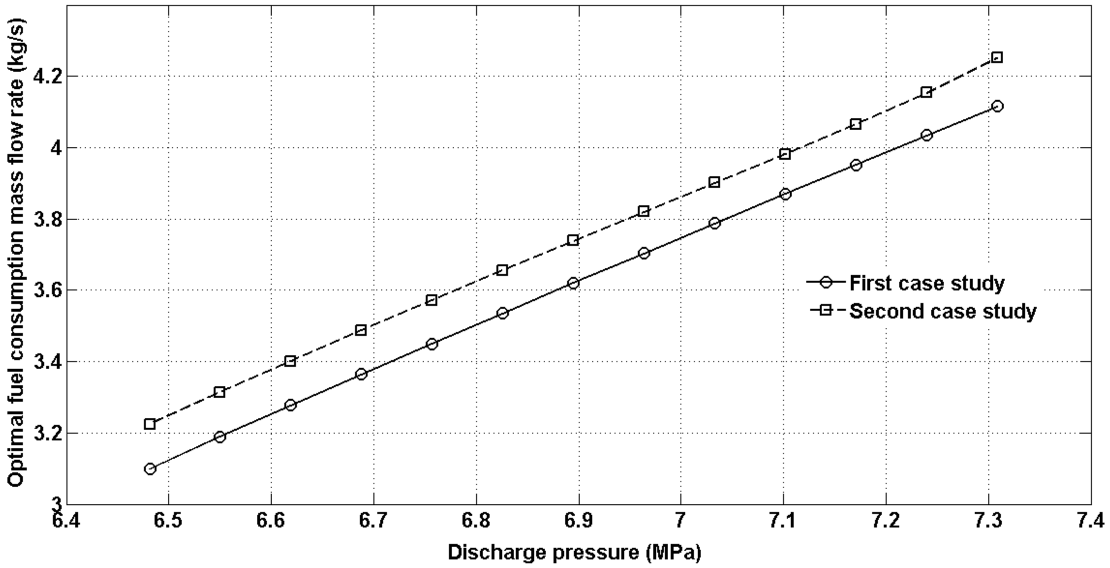

Surge line
Maximum speed line
Isentropic Head(J/kg)
Qmin
Qmax
Minimum speed line
Stonewall line
Actual volumetric flow rate(m3/s)


Start
Input data: $p_s, T_s, p_d, Q_{station}$
Compute H using Eq (3).
For the specified value of H, compute Q_{min_i}, Q_{max_i} for each compressor based on its operating map (as shown in Figure (4)).
Compute utilization: $\alpha = \frac{Q_{station}}{\sum_{i=1}^{n} J_i \cdot Q_{\max_i}}$
Compute rate of flow passing through each unit:
$Q_i = J_i \cdot \alpha \cdot Q_{\max_i}$; $i \in \{1, 2, \ldots, n\}$
Is $Q_{min_i} \leq Q_i \leq Q_{max_i}$ or $J_i = 0$?
$\left(i \in \{1, 2, \ldots, n\} \right)$
No
Infeasible solution
Yes
Compute fuel consumption of each unit ($\dot{m}_{f_i}$) as a result of simultaneous solution of Eqs (1) to (16)
Compute station fuel consumption: $\left(\dot{m}_f\right)_{station} = \sum_{i=1}^{n} J_i \cdot \dot{m}_{f_i}$
End


Start
Formation of the first generation: Randomly choosing 0 or 1 for each bit
Example:
Chromosome 1
1 0 … 0
Chromosome 2
0 1 … 1
⋮
Chromosome n
1 1 … 1
Objective function evaluation: Computing objective function for each chromosome (solution)
Is the stop criteria satisfied?
Yes
End
No
Selection: Randomly selecting n pairs of chromosomes for creating the new generation (chromosomes with better objective functions have a greater chance of being selected).
Crossover: Producing offspring that inherit its genes from both parents.
Example:
1 0 1
0 1 0
1 1 0
Mutation: Altering value of each bit of offspring from 1 to 0 or vice versa with the probability called mutation probability.
Example: one bit mutated.
1 1 0
0 1 0


Optimal fuel consumption mass flow rate (kg/s)
5.5
5
4.5
4
3.5
3
2.5
2
100
110
120
130
140
150
160
170
180
190
200
Compressor station volume flow rate (MMSCMD)
First case study
second case study


Optimal fuel consumption mass flow rate (kg/s)
5
4.5
4
3.5
3
2.5
5
5.1
5.2
5.3
5.4
5.5
5.6
5.7
5.8
5.9
6
Suction pressure (MPa)
First case study
Second case study


Optimal fuel consumption mass flow rate (kg/s)
3
3.2
3.4
3.6
3.8
4
4.2
6.4
6.5
6.6
6.7
6.8
6.9
7
7.1
7.2
7.3
7.4
Discharge pressure (MPa)
First case study
Second case study