Genetic Algorithm Optimization of Fuel Consumption in Compressor Stations

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Abstract: - Natural gas passing through pipelines is transported via compressor stations. These stations are usually installed at above 60 miles away from intervals in order to overwhelm the pressure loss generated through the friction or the heat exchanging. Different compressors have been utilized in these stations to acquire the constraint gradient pressure and maintain the required mass flow rate at the delivery. A considerable proportion of the transported gas is however consumed to supply the drift force. Since currently millions of MMSCFD gases are transferred between countries, it seems indispensable to propose a precise model to minimize the consumed fuel and to stumble on suitable decision-making variables.

This paper analyzes non-linear mathematical relationships which are required to evaluate the steady, isothermal, one-dimensional and compressible flow inside the pipes. In the next stage, the study establishes the equations associated to the compressor performance and it finally evaluates the rate of fuel consumption in the power generator. The activities are divided into two categories: a) simulation by means of the computational modules, related to the fluid specifications and the main components of the transmission system, b) amelioration through the exploitation of the optimization methodology using genetic algorithms. Spread sheets are utilized as useful tools to establish a relationship among the aforementioned sections and the analysis of the system comportment. The optimization modeling aims to improve the fuel consumption in the compressor stations available in the network commensurate with the stipulations of the transmission system.

Key-Words: Optimization, Genetic Algorithm, Compressor Station, Fuel Consumption, Spread Sheets

1 Introduction

One of the highly efficacious contraptions availed in making designs, performance and optimization studies is the mathematics modeling. Users have ferreted out the feasibility of utilizing software packages, online analysis of the leakage spots, multiphase flows, optimization, guaranteeing the flow safety, and so on. Nonetheless the utilization of the steady state analysis methodology and tools are quite popular due to simplicity of the analysis and the utilitarian nature of results. Stacks of researchers are exerting themselves to happen upon ways of optimizing gas transmission procedure based upon the functions of the pipelines and the most complicated component of the transmission system yclept the compressor stations.

Henry Hain took measures in 1977 to delve into the feasibility of utilizing steady contraptions to analyze the transient flows [1]. McClure used the linear programming methodology to break down the pipe lines in an optimized manner in natural gas organization in Michigan Wisconsin in 1982[2]. Genetic algorithms were employed for the first time in 1985 for the optimization of the pipelines [3]. Howard and Murphy, personnel of the natural gas transmission organization in Columbia presented a methodology for modeling the performance of compressors to upgrade their functionality and the quality of the decisions adopted for optimization [4]. Fred Odom et al members of a solar turbine manufacturing corporation presented two diverse versions for modeling gas turbines which activate centrifugal compressors [5]. Samuel Andrus wielded the spread sheets for the first time in 1994 to simulate the steady state gas transmitting pipes and network stipulating that the compressibility factor is constant for all the systems [6]. The aforementioned methodology was executed once again by Ian Cameron from Trans Canada in 1999 to examine both steady and transient flows in Excel software[7]. Chapman & Mohammad Abbaspour from Kansas varsity have made abundant perusals in the fuel optimization methodologies in compressor stations in the non-isothermal and transient conditions using compressors shafts velocities as a decision-making variable [8].Computational contraptions have been utilized to pave the way for the development and the revamping of the complicated systems. The burdensome nature of such calculations can be regarded from several aspects: 1. The compressor stations available in the network have intricately complicated comportment because diverse and numerous active and inactive compressors with disparate configuration and specifications may have been installed in each station; 2.A set of complicated nonlinear equations has to be formed to determine the operational points assigned for the optimization and compatible with the function of compressors, gas turbines, pipelines, connections and their constraints or set points. The items scrutinized in this article comprise the extraction of the algebraic relations from the continuity and momentum equations, accessing the generic equations of the flow inside pipes, determining the pressure of the compressible fluid, confabulating about the manners of working out the compressibility and friction coefficients dynamically and the equations pertinent to the performance of the centrifugal compressors. The aforesaid relationships have been plied in the computational modules to particularize the specifications of the passing fluid, pipe, dividing and junction connections, compressor and turbines to simulate the transmission system. The methodology and the grounds for the utilization of the target function and the decision-making variables as well as the revamping algorithm of section B have been illustrated by exemplifying an instance concerning the optimization of the fuel consumption in a network which encompasses 2 compressor stations.

2 Problem Formulation

2.1 Pipeline

The differential formula for the momentum equation for the natural gas passing through pipes in steady state, isothermal and single phase conditions:

$$\frac{1}{\rho}\frac{\partial P}{\partial x} + g\frac{dy}{dx} + v\frac{\partial v}{\partial x} + 2\frac{fv^2}{D} = 0 \quad (1)$$

Simplification of the aforementioned equation claims the ensuing formula. It is evident that the aforesaid relation comprises four terms known as pressure dropping, elevation, kinetic energy, and the friction pressure loss.

$$\frac{\partial P}{\rho} + gdy + \frac{v\partial v}{\alpha} + 2\frac{fv^2}{D}dx = 0 \quad (2)$$

Differentiation of the gas local velocity relationship and the insertion of it together with the equation of the state of gas in the foregone relation (2), simplification and deletion of the kinetic energy, elevation terms, into volumetric flow relationship in standard conditions figured out by the gas technology institution are obtained (AGA).

$$Q_g = \left(\frac{\pi}{8}\right)\left(T_{sc}/P_{sc}\right)\left(\frac{\bar{R}}{28.97}\right)^{0.5}\left(D^{2.5}\Big/\sqrt{fZT\gamma_g L}\right)\left(P_i^2 - P_j^2\right)^{0.5} \quad (3)$$

Insertion of the generic type of the friction coefficient based upon Reynolds number and the term-prone definition entitled Ep (pipe efficiency), results in the simplification of the flow and press correlation in isothermal, steady state and single phase, circumstances irregardless of the elevation terms and the kinetic energy.

$$Q_g = a_1 E_p\left(T_{sc}/P_{sc}\right)^{a2}\left[\frac{\left(P_i^2 - P_j^2\right)}{TZL}\right]^{a3}\left(1/\gamma_g\right)^{a4} D^{a5} \quad (4)$$

Equation	a_1	a_2	a_3	a_4	a_5
Panhandle	435.73	1.0788	0.5394	0.4604	2.6182
IGT	434.28	1.1110	0.5560	0.4444	2.6667
Weymouth	433.50	1.0000	0.5000	0.5000	2.6667

Table 1: Coefficients of the generic flow equations

The pressure quantification along the pipelines alias P_i is materialized through meshing of each section of the pipeline and sundering them into i equal sections while employing the relation (4).

$$P_i = \sqrt{P_1^2 - (i-1)\sqrt[a_3]{C_1}} \quad (5)$$

$$C_1 = \frac{q_g (TZ\Delta x)^{a_3}}{a_1 E_p \left(T_{sc}/P_{sc}\right)^{a_2} (1/\gamma_g)^{a_4} D^{a_5}} \quad (6)$$

Some persistent endeavors have been made to make turbulent regime in gas transmission systems. The aforementioned relationship yields diverse results within Reynolds limits. Some of the upshots are quite disparate from local measurements. That is why $(a_1....a_5)$ coefficients have been classified within dissimilar Reynolds for tubes bearing contrastive diameters based upon the Table 1, [9]. Since 24-inch diameter tubes have been utilized in the extant specimen, optimum sequels will be obtained in case Weymouth coefficients with regard to the limitations of the these relationships are taken into account. It should be noted that $E_p \approx 1$ is required in the aforementioned relation in NPS36 tubes. Considerable friction reduction transpires in the deviation friction coefficient which can be rectified through the utilization of the relation (7):

$$\sqrt{1/f} = \frac{11.19}{2} D^{0.167} E_p \quad (7)$$

We utilize AGA relation to figure out the quantities of the volumetric or mass flow rates in intersections.

2.1.1 Friction coefficient calculation procedure

Friction factor is one of the significant parameters to work out the pressure loss due to the fluid friction inside pipes in the flow equation. The alterations of the aforesaid factor can be categorized in four diverse regimes in rotating pipes in dissimilar Reynolds and roughness which are as follows: Laminar flow (Re), turbulent flow within polished wall (Re), turbulent flow with semi-rough wall (function of Re and the relative roughness) and eventually turbulent flow with thoroughly rough wall (function of the relative roughness). Hence, this factor is appraised in two positions alias polished and rough pipes. Since deviation quantity in Colebrook-White Relation has been rectified, Reynolds lower than 2000×10^8 are less than 0.068 in the aforementioned two positions. Since the foregone relation is implicit, an optimum result can be extracted out of the Moody diagram by availing the reiterative solution methodology:

$$f^{-0.5} = 3.48 - 4\log\left(\frac{2\varepsilon}{D} + \frac{9.35}{f^{0.5}\,\mathrm{Re}}\right) \quad (8)$$

2.2 Compressibility calculation procedure

The above factor is the contrastive deviation of the volumetric comportment of a real fluid collated with an ideal fluid volumetric behavior. This is one of the most momentous parameters to devise natural gas systems. Standing-Katz Chart is the most crucial methodology to determine the compressibility factor in gases. Diverse computerized procedures have been proffered for modeling this chart during the past years. Dranchuk methodology has the least errors out of them [10]. The relations they used for the calculation of the above factors are as follows:

$$Z = 1 + c_1\rho_r + c_2\rho_r^2 + A_9 c_3 \rho_r^5 + A_{10}\left(1 + A_{11}\rho_r^2\right)\left(\rho_r^2 / T_r^3\right)\exp[-A_{11}\rho_r^2] \quad (9)$$

c_1, c_2 and c_3 coefficients, density, temperature and the reduced pressure parameters have been presented as follows:

$$c_1 = \left(A_1 + \frac{A_2}{T_r} + \frac{A_3}{T_r^3} + \frac{A_4}{T_r^4} + \frac{A_5}{T_r^5}\right) \quad (10)$$

$$c_2 = \left(A_6 + \frac{A_7}{T_r} + \frac{A_8}{T_r^2}\right) \quad (11)$$

$$c_3 = \left(\frac{A_7}{T_r} + \frac{A_8}{T_r^2}\right) \quad (12)$$

$$\mathrm{Pr} = \frac{P}{P_c}, T_r = \frac{T}{T_c}, \quad \rho_r = \frac{0.27P_r}{ZT_r} \quad (13),(14),(15)$$

Kay's Rule has been applied to work out the term of the critical pressure and temperature. $(A_1....A_{11})$ coefficients have been extracted from Standing-Katz Chart for the aforementioned relations.

It is evidence in Fig.5 that in case Newton-Raphson numerical methodology is employed to figure out the reduced density term, the compressibility factor will be obtained precisely as expected. It should be noted that the above relation is applicable within reduced pressure $0.2 \le P_r < 30$ and reduced temperature $1.0 < T_r < 3.0$ range. Out of these limitations the calculation precision of the compressibility factor deviates.

2.3 Centrifugal compressor

Centrifugal compressors have been bound within Choke, Stonewall limits at the bottom of the map, Surge and Stall scope at the top of the map as well as the minimum and maximum shaft rotation speed. Compressor will undergo irreparable losses in case above quantities are outstripped. Thus the optimization calculation precision has to be executed in a way that does not transcend the above limits and the minimum feasible working conditions of the compressor. Therefore, q_{ac}/ω, η and $Head/\omega^2$ ratios have been designated to establish a mathematical model of the compressor's map entity. The numeric procedure (least square method), has been employed to figure out the constant coefficients of the ensuing relations:

$$\frac{Head}{\omega^2} = A_h + B_h\left(\frac{q_{ac}}{\omega}\right) + C_h\left(\frac{q_{ac}}{\omega}\right)^2 \quad (16)$$

$$\eta = A_e + B_e\left(\frac{q_{ac}}{\omega}\right) + C_e\left(\frac{q_{ac}}{\omega}\right)^2 \quad (17)$$

Compressor's map entity in field conditions is extracted from Excel data by means of Plot-digitizer software to work out the coefficients (Fig.3). The least square module (Ls.xla) is utilized upon the foregone ratios to yield the coefficients in question (Fig.4). By the utilization of Head and one of ω or q_{ac} quantities the third magnitude required in relation (17) is obtained in accordance with (16) relation and the compressor efficiency will be obtained afterwards. The stipulations of the minimum and maximum velocity and the volumetric flow rate can be easily applied upon the set of the above relations.

$$Head = \left(\frac{k}{k-1}\right) ZRT \left(\left(\frac{P_d}{P_s}\right)^{\left(\frac{k-1}{k}\right)} - 1 \right) \quad (18)$$

The break power and required compressor shaft power can be computed by means of relation (19).

$$PWR = \frac{32.174 \times W \times Head}{\eta \times \eta_{mech}} + Al \quad (19)$$

2.4 Gas turbine

In case we counterpoise the compressor required power and the generating power of turbine, the fuel consumption quantity of the gas turbine can be computed in diverse operational circumstances. It is evidence in the ensuing relations that the required PWR of compressor has been employed to compute the generating power of the gas turbine and the fuel consumption rate. Hence, the turbine fuel quantity will be given forth in terms of $[SCF/Sec]$.

$$APWR = (1 - ARF(T_A - T_R)) \times RPWR \quad (20)$$

$$FAP = PWR/APWR \quad (21)$$

$$\eta_D = \frac{\eta_{\mathrm{Re}}}{\left(A_{DE} + B_{DE} \times FAP + C_{DE} \times FAP^2\right)} \quad (22)$$

$$FC = PWR/(\eta_D \times HV) \quad (23)$$

3 Simulation components

The calculation modules matching the major system elements have been concocted by means of the Excel software programming environment (Visual Basic). The inputs and the calculation upshots can be summoned and displayed in the spread sheets. Spread sheets are useful contraptions for comprehending the shifting and simulation systems. Samuel Andrus & Ian Cameron utilized Excel software respectively in 1994 and 1999 to simulate the steady state flow the constant nature of the compressibility factor in the whole system and the simulation of steady state and transient natural gas flows respectively [6],[7]. The topic of the rest of the activities in this regard concerns the current simulation in the steady mode to minimize the fuel consumed inside the compressor stations through nonlinear optimization techniques. Some of the advantages of utilization of this system comprise the exploitation of the whole facilities of Excel, the reiterative calculation feasibility, working out equations with numerous parameters and the concoction of xla functions and subroutines. The modules developed in this section are as follows:

Pipe_press: this module is utilized to work out the pressure loss in the segments of pipeline.

Pipe_Eff: It extracts the friction coefficient from the Moody diagram by means of the implicit relation (8) and computes the efficiency of the corresponding pipe whose diameter and coefficient have been figured out.

Dividing: It calculates the volumetric flow rate and the pressure of the branch pipes at the connection site of the main pipe by application of the mass balance relation.

Combining: It computes the volumetric flow rate and the counterpoised pressure of the input branches of a spot.

Turbo_compres: The quantification of temperature, volumetric flow rate, the output pressure of compressor as well as all the computations of the generator including the fuel consumption of the gas turbine are carried out in this module.

Ug and **Z**: These modules involve the calculations pertinent the properties of the natural gas passing through the network. Compressibility factor has been created in accordance with the flow chart as exemplification.

4 Optimization

When centrifugal compressors are set into motion by gas turbines, they may initiate diverse operational circumstances through velocity control. This is one of the most natural manners of controlling the transmission system on account of the fact that centrifugal compressor and 2-shaft gas turbines can function on a wide range of velocities (even 50% less than the utmost velocity). Having determined the flow rate (by means of a tool like orifice, venturi nozzle, infrasonic equip, etc), the controller can alter the fuel flow in case any change in the output or input pressure transpires. Thus, the gas turbine will produce energy commensurate with the consumed fuel and instigates the decrease of the compressor rotation. Hence, it is quite worthy to opt for the compressor rotation velocity as a decision-making variable. The consumption rate of the gas turbine fuel relation can be plied to determine the target function. Hence, counterpoising the power initiated in the gas turbine with the required energy to materialize the set points and constraints of the compressor and transmission system. The beneath relationship can be simplified based upon the decision-making variable.

$$\min \sum_{i=1}^{n} FC(\omega_i) = \min \sum_{i=1}^{n} \frac{PWR_i}{\eta_{Di} \times HV} \qquad (24)$$

4.1 Constraints and limitations

It can be easily discerned that the relation (24) is nonlinear owing to interdependency of the driver efficiency terms and the compressor power as altered by the decision-making variable. Thus the quantitative amounts of the fuel used up in stations can be worked out by exertion of appropriate restrictions. The restrictions of the nonlinear programming play a pivotal role to ensure fruitfulness and to eschew awful action while seeking to happen upon an optimized operational point. It should be noted that in this particular case, the system compressors can only function within the velocity range and the flow rate devised for them. Another stipulation applied to ensure the mass flow rate passing through the station evinces the flow rate required in the next station or the delivery point.

The optimization of the pipeline function can be expounded based upon the aforementioned subjects as follows: i is regarded as the counter of the compressors inside a station and ω_i is the rotation velocity of the i_{th} compressor available in the station. Thus $\min \omega_i$, $\max \omega_i$ are respectively the minimum and the maximum permitted rotation velocity of the i_{th} compressor. $\min q_{ac,i}$, $\max q_{ac,i}$ are the approximate rate of the flow passing through compressor. $\dot{m}_{\min}$ is the minimum permitted passing-through flow rate of the station. It should be noted that $\dot{m}_f$ is the objective function and equal to the fuel consumed in the turbines of transmission system.

4.2 Conditions affecting the optimization algorithm selection

The complexity of the network components, the largeness of the search and design spaces (a set of feasible responses), the numerous conditions and circumstances of the problem which any of them are not materialized, irreparable damages will be inflicted upon the system and the lack of awareness as regards the inchoation points in the optimization process are the important specifications of this selection. Optimization process is designated as settling upon the best reply out of the ones available in the design system. The search process can be carried out in two methods: deterministic search and stochastic search which are effectuated like random base algorithms. Considering the quandary's conditions, the utilization of the stochastic methodology instigates the curtailment of the search space and the simplification of the relationships affecting optimization.

The genetic algorithm (GA) has been examined in this article as one of the stochastic patterns based upon the random processing. As mentioned earlier, GA was first applied for the betterment of the natural gas transmission pipelines in transient condition, in 1985. Goldberg utilized this algorithm in 1987 to ameliorate steady serial line pipe and single transient line pipes by zooming on minimization of the search space and the selection of the appropriate mutation and crossover rates [12]. Nonetheless Carter set the above algorithm in the less significant priorities in 1988 owing to the sensitivity of algorithm with regard to diverse selection methods, mutation and crossover rates[13].

Here we examine the acceptance of utilizing GA to gain fast access to the optimized quantities based upon our modular and simulation base views.

4.3 Genetic algorithm

Genetic algorithm is a branch of the evolutionary algorithms which has been established based upon the "survival of the best" and "the proliferation of the superior species" as inspired by Darwin evolutionary hypothesis. This algorithm's operation is based upon a haphazardly guided trend as one of the indiscriminate optimization methods. An abstracted sample of candidates for solving (chromosomes) can claim a better solution in such algorithms. The design space has been created with a random populace of strings (which are 0 and 1 here) and these strings recur in generations. The whole population has been appraised in each generation. Some chromosomes have been opted based upon the objective function or the cost function out of the extant generation. Having being affected by other operators they supersede the extant generation in the ensuing reiteration. The optimized results are obtained based upon one of the prevalent stoppage criteria: 1) the algorithm implementation time; 2) the number of generations procreated; and 3) the convergence of the error criteria. Advantages of utilizing GA can be discussed in several perspectives:

- The design space is converted into the genetic space which is the encoded space in this algorithm. Thus it will become feasible to transfigure the incessant huge spaces into disjointed tiny ones which are utilized to solve the optimization quandary here.
- GA interacts with a particular set of points whereas we focused upon a specific point in most optimization methods. In other words, GA processes multiple possible responses which eventually enable us to access the available optimum responses in the end of optimization.
- This algorithm is based upon the guided haphazard process; therefore, its utilization in the pertinent nonlinear problem does not make it entrapped in the local optimum spots.

The trend of this algorithm can be displayed in accordance with the Fig.6.
The corresponding quantities of the decision-making variables of the problem alter their nature incessantly between the genetic space code and the response. The response space can be identified either as diverse numerical combinations different from the decision-making variable or the velocity of the compressors available in the network.

$$j = \{\omega_1^j, \omega_2^j, \ldots\ldots, \omega_n^j\} \tag{25}$$

The code space is made up of the binary-structured chromosomes. The k quantity is computed based upon Locus's span or the difference of the velocity limitations of each chromosome to determine the length of chromosomes available in this space.

$$\omega_i^L < \omega_i < \omega_i^U \tag{26}$$

$$S_i = \omega_{i,\max} - \omega_{i,\min} \tag{27}$$

$$S_i < 2^{k_i} \tag{28}$$

There are k bits required to encode S in the binary coding methodology. The response chromosomes will be depicted as Fig.1 eventually.

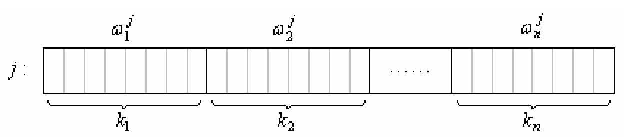

Fig.1: Shape of each chromosome

Here we have stipulated the k_i quantities equal to each other and counterpoised to the largest one. Each ω can be computed based upon the ensuing formula:

$$\omega_i = \omega_i^L + \frac{S_i}{n \times k_i}(Coded.Variable) \tag{29}$$

Diverse methodologies can be envisaged for operators available in the code space. Here, Tournament method is used for the reproduction operator in this particular quandary. In other words, a small set of chromosomes are picked out haphazardly to compete with each other. One of the chromosomes is copied as a generator in the mating pool based upon the fitness or the evaluation score. Then crossover operator acts upon chromosomes available in the mating pool in accordance with the two-point cut methodology and the contents of the two chromosomes are swapped by singling out two indiscriminate spots.

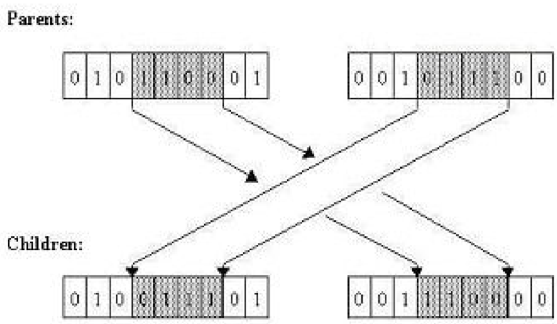

Fig.2: Crossover tow-point cut operator

It should be noted that the crossover operator rate and the mutation operator rate are respectively 0.6 and 0.01 after several reiterations of the experiment in a real network.

5 Case study

As a case study, the parameter of best operational points in the compressor stations of a typical small network with minimum rate of fuel consumption was established. In this network, the natural gas with relative density of 0.6, molecular weight of 17.382 lbm/lbm.mol at 125.6$^\circ F$ and 129105 lbf/ft^2 pressure flowed through two stations including 3+1 parallel centrifugal compressor with the different performance map. The diameter of pipe is 24 inch through the length and relative roughness is 0.0007 inch .Minimum and maximum of centrifugal operation speed is 150-235 rev/sec. The discharge pressure and mass flow rate at delivery point are

106237 lbf/ft^2 and 370.38 lbm/sec. GA is used to find the optimal speeds of all six active compressors simultaneously. Table2 indicates some of the system results, before and after optimization process.

	Initial Value	After Opt.
Station 1		
1st Comp. Speed	213.25 rev/s	207 rev/s
1st Comp. Efficiency	80.31	80.2
2ed Comp. Speed	191.75 rev/s	186.25 rev/s
2ed Comp. Efficiency	78.5	78.1
3ed Comp. Speed	180 rev/s	178.15 rev/s
3ed Comp. Efficiency	77.61	77.58
Station 2		
1st Comp. Speed	213.25 rev/s	206.9 rev/s
1st Comp. Efficiency	80.31	80.16
2ed Comp. Speed	191.75 rev/s	187 rev/s
2ed Comp. Efficiency	78.5	78.34
3ed Comp. Speed	180 rev/s	178.05 rev/s
3ed Comp. Efficiency	77.61	77.56
Throughput and Fuel Consumption		
Mass Flow Rate	377.87 lbm/s	370.42 lbm/s
Fuel Consumption (lbm/s – MMSCFD)x10^3	186 - 350.87	170.13 - 320.92

Table 2: Simulation results before & after Optimization

The case study clearly indicates the effectiveness and ease of use in the actual application of the developed and implemented methodology.

6 Conclusion

In the first stage, the main components of the natural gas transmission systems were modeled and the appropriate mathematical relations were extracted. In the second stage, lines and the compressor stations have been simulated taken into consideration some of the facilities of spread sheets. Using modular programming techniques and Genetic Algorithm, the operational optimized points in fuel consumption were generated. The model was further applied to a case study and best operational points with the minimum rate of fuel consumption were established for a typical compressor station.

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Appendices

Nomenclature

$A_1 ... A_{11}$	Dranchuk-Abou-Kassem's Z-equation coefficients $(-)$
$a_1 ... a_5$	Constant pipe coefficient $(-)$
A_{de}, B_{de}, C_{de}	Driver efficiency coefficients $(-)$
A_e, B_e, C_e	Efficiency coefficients determined by polynomial fit $(-)$
A_h, B_h, C_h	Head coefficients determined by polynomial fit $(-)$
Al	Auxiliary load $(ft.lbf/\sec)$
$APWR$	Available Power $(ft.lbf/\sec)$
ARF	Ambient rating factor $(1/°R)$
D	Diameter of the Pipe (ft)
E_p	Pipe Efficiency $(-)$
FAP	Fraction of available power $(-)$
f	Friction factor $(-)$
FC	Fuel consumption $(scf/\sec)$
g	Gravitational acceleration $(ft/\sec^2)$
$Head$	Isentropic Head $(ft.lbf/lbm)$
HV	Heating Value $(ft.lbf/scf)$
k	Number of bits in binary coding
L	Length of the Pipe (ft)
P	Pressure of the Gas (lbf/ft^2)
PWR	Power $(ft.lbf/\sec)$
Q	Volumetric Flow $(ft^3/\sec)$
$\overline{R}$	Universal Gas constant $(-)$
Re	Reynolds Number $(-)$
$RPWR$	Rated power $(ft.lbf/\sec)$
S	Locus's span $(-)$
T	Temperature $(°R)$
v	Velocity of the Gas $(ft/\sec)$
W	Mass flow rate $(slug/\sec)$
Z	Compressibility factor $(-)$

Greek Letters

α	variation in the velocity profile over the pipe cross-section $(-)$
Δ	Loss
ε	Internal Roughness (ft)
η	Efficiency $(-)$
γ_g	Specific gravity $(-)$
ρ	Density of the Gas $(slug/ft^3)$
σ	Ratio of specific heats $(-)$
ω	Speed $(rev/\sec)$

Subscripts

A	Ambient
ac	Actual condition
c	Critical
D	Driver
$mech$	Mechanical
r	Reduced
R	Rated
sc	Standard condition

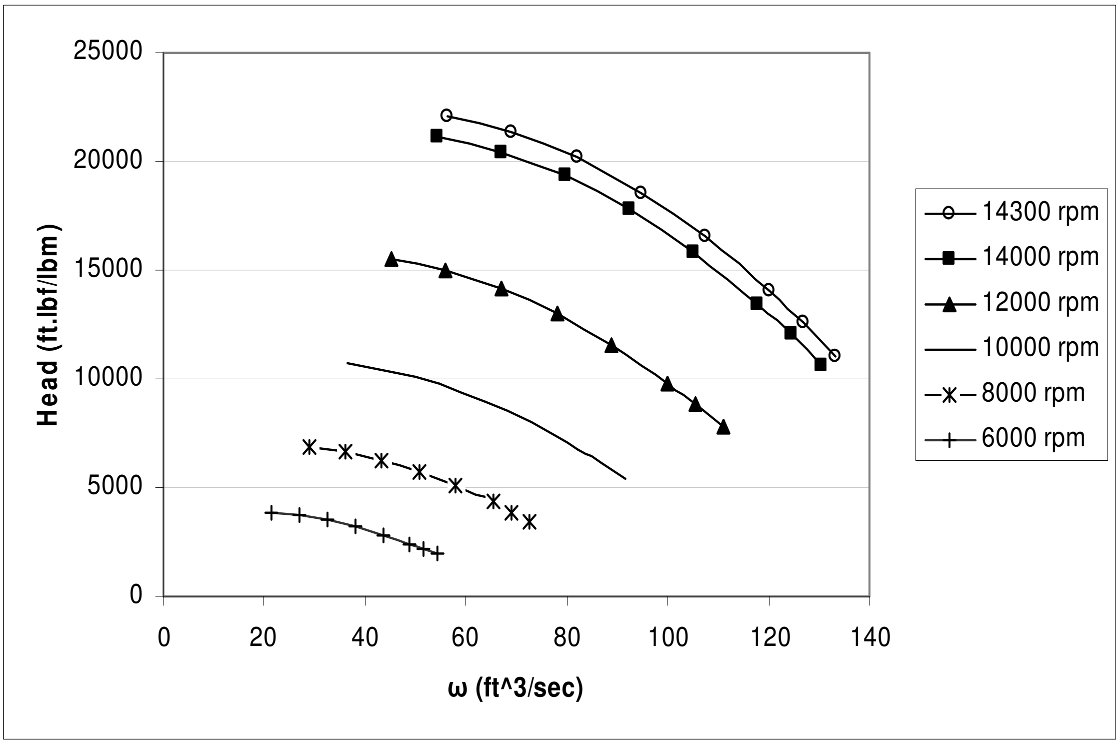

Fig.3: Single centrifugal compressor map

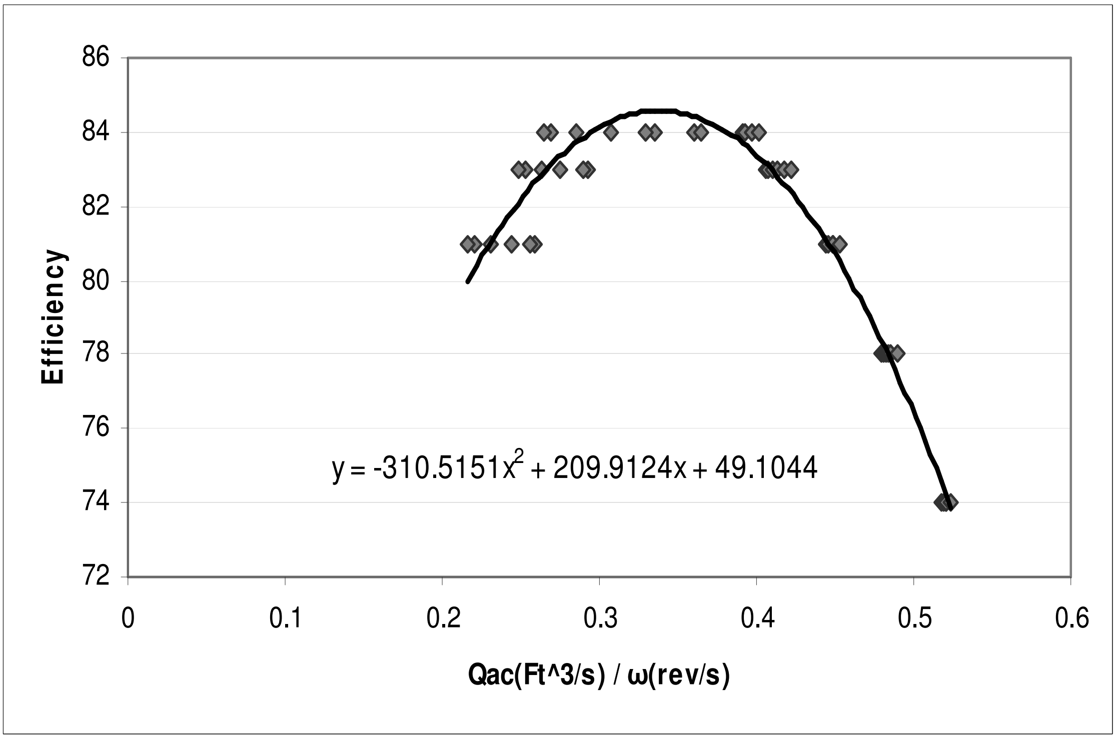

Fig.4: Compressor efficiency as a function of Q_{ac}/ω

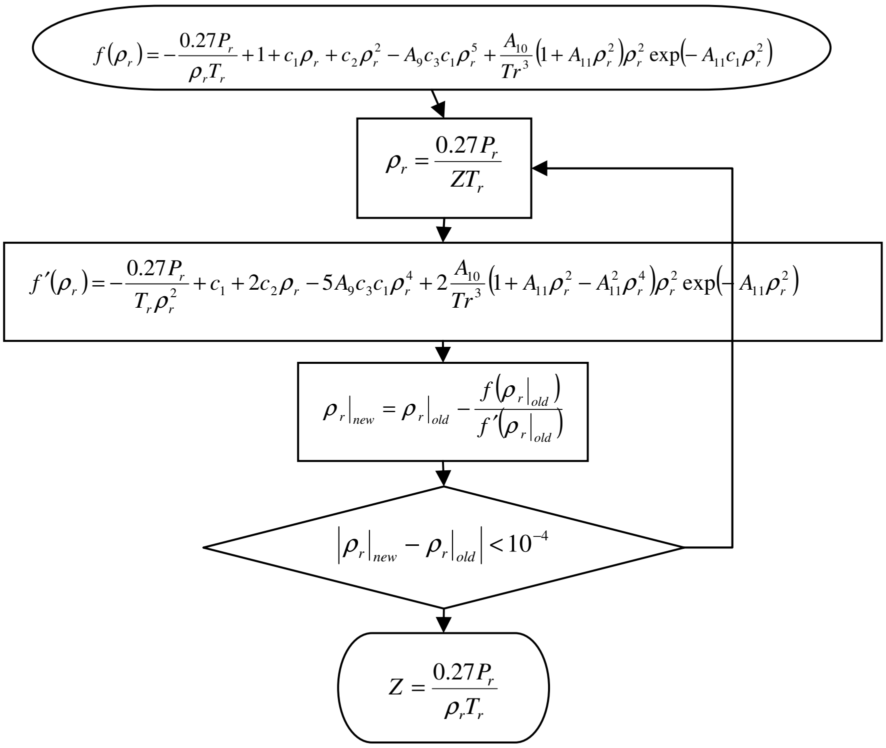

Fig.5: Compressibility factor calculation procedure

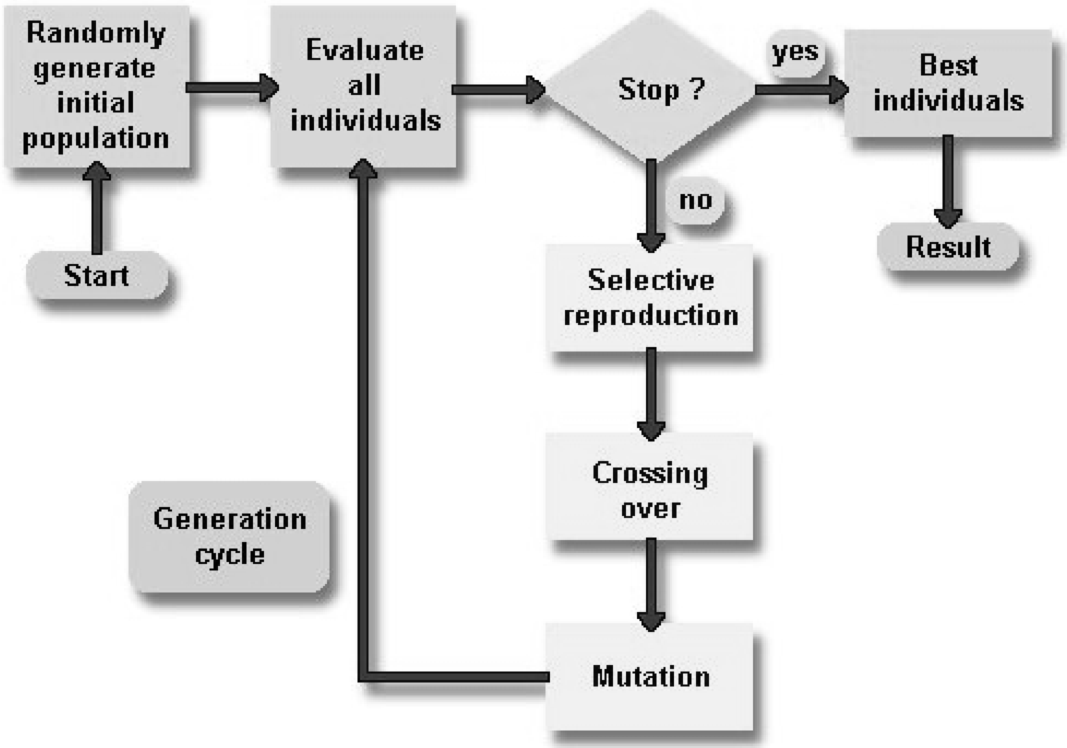

Fig.6: Genetic algorithm optimization procedure