OPTIMAL DESIGN OF GAS DISTRIBUTION NETWORK: A CASE STUDY

التصميم الأمثل لشبكة توزيع الغاز : دراسة حالة

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الخلاصة:

يعد الغاز الطبيعي وقوداً صديقاً للبيئة كون أنه اقل أنواع الوقود العضوي انبعاثاً للسموم، بيد أنه أكثر ما يؤثر على تكلفته هو تكلفة شبكات نقله وتوزيعه، ومن ثم فحري بنا أن نقلل من التكلفة الكلية للغاز ليكون رخيص للتداول. هذا العمل الذي نحن بصدده يهدف إلى تطوير برنامج كمبيوتر لمحاكاة وتعظيم شبكات توزيع الغاز الطبيعي، الهدف هو تقليل أقطار مواسير الشبكة مع الحفاظ على عدم تعدي السرعة في المواسير الحد الأقصى، وعدم تعدي الضغط في نقاط التوزيع الحد الأدنى. في هذا البحث، استخدمت طريقة التدرج (gradient algorithm) لتحليل الشبكة هيدروليكيا، واستخدمت طريقة الخوارزميات الجينية (genetic algorithms) لتعظيم الشبكات، وقد تم تطبيق هذا البرنامج على شبكات ضغط قليل وضغط متوسط وقد أثبتت فاعليتها. فى هذه الدراسة تم التطبيق على شبكة غاز طبيعي حقيقية هى شبكة توزيع الغاز بمحرم بك بمدينة الأسكندرية. ولقد قام البرنامج باختيار أمثل أقطار لأنابيب الشبكة بحيث يحقق أقل تكلفة مع الوفاء بجميع متطلبات الشبكة من استهلاكات وضغوط مختلفة.

ABSTRACT

One of the major parameters that affect the price of natural gas is the cost of its transmission and distribution networks. So it's valuable to reduce its total cost to be affordable for individual customer. Gas networks optimization is raised to focus on the network cost regarding to its design parameters after the revolution in personal computers.

This work is a step towards developing a computer code that simulate and optimize gas distribution networks at all networks pressure ranges, i.e. low, medium and high pressure networks. The aim is to reduce the network diameter sizes to a minimum value while fulfilling the constraints of maximum flow velocity and minimum node pressure.

In this work, the gradient algorithm is used to solve the hydraulics of the networks, which had never presented in gas networks before. The algorithm was fulfilled and gave an efficient analysis for all gas networks, i.e. at all pressure ranges, at the least time any algorithm can record. Optimization of gas distribution networks was presented by the genetic algorithm. The code was applied on low and medium pressure gas distribution networks and proved its efficiency and robustness. Therefore, this code is applied to a case of an existing network in the actual life in Egypt. It is a part of Moharram-Bek gas distribution network in Alexandria City, Egypt. The developed code released the network analysis for the already designed network, and the optimization data for the network which fulfilled the required constraints.

Keywords: Gas Network, Optimization, Genetic Algorithm, Cost, Steady-state, Case study

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1. INTRODUCTION

Until recently, the study of gas networks was focused on the development of efficient methods for analyzing the networks hydraulics for existing and proposed distribution networks, Osiadacz [1], Osiadacz and Górecki [2], and Herrán-González et al. [3].

Due to the increasing demand on constructing pipe networks to transmit and distribute natural gas all over the worlds, the cost of pipe networks becomes a challenge task. Recently, optimization is used to minimize the cost of natural gas networks.

The gas network optimization can be divided into two main categories: the optimization of gas transmission pipelines and the optimization of gas distribution networks. The researches mainly focused on gas transmission pipelines optimization due to the high cost of equipments (compressor stations, reduction-valves stations and pipelines), and the low capability of computers to optimize gas distribution networks at beginning period of optimization researches.

The distribution network differs from the transmission one in its small-diameter pipes, its simplicity as there are no valves, compressors or nozzles, and its operation at low and medium pressures. The main interest in this study is focused on distribution networks.

The optimization of gas networks means searching, according to a certain objective function. The cost of low and medium pressure networks depends mainly on network capital cost, whereas the cost of high pressure is determined mainly by mode of operation of compressors. This operating cost of running compressor stations represents 25% to 50% of the total company's operating budget (Osiadacz [4]) which consumes over 3% to 5% of total gas transported, (Wu et al. [5]).

Larson and Wong [6] determined the steady-state optimal operating conditions of a straight pipeline with compressors in series using dynamic programming to find the optimal suction and discharge pressures. The length and diameter of the pipeline segment were assumed to be constant. Martch and McCall [7] modified the problem by adding branches to the pipeline segments.

O'Neill et al. [8] introduced a problem of a transmission through compressor stations, including the optimization of the operation scheme. They used Successive Linear Programming in optimization.

Olorunniwo and Jensen [9] provided further breakthrough by optimizing a gas transmission network including the type and location of pipelines and compressor stations. Edgar and Himmelblau [10] simplified the problem addressed in [9]. They optimized the number of compressor stations, the pipe length, diameters and the suction and discharge pressures. They considered minimizing of the total cost of operation per year.

Osiadacz [4] published a paper for the operation optimization for high pressure transmission lines.

De Wolf and Smeers [11] used the problem of O'Neill et al. [8] using piecewise linear programming. De Wolf and Smeers [12] continued the problem and represented the piecewise linear approximations as "special ordered sets of type 2" so that the piecewise linear problem could be globally solved by a mixed-integer programming.

Ríos-Mercado et al. [13] proposed a reduction technique for minimizing the fuel consumption incurred by compressor stations in steady-state natural gas transmission networks.

Babu et al. [14] applied the differential evolution for the optimal design of gas transmission network.

Pietrasz et al. [15] studied the problem of reinforcing regional gas transmission networks to cope with the forecasted demand for natural gas.

André et al. [16] solved the problem of minimizing investment costs on an existing gas transportation network by finding the optimal location of pipeline segments to be reinforced and the optimal sizes.

Chebouba et al. [17] proposed an ant colony optimization algorithm for operations of steady flow gas pipeline.

For the gas distribution networks optimization, the improved capabilities of PCs in the beginning of 1980s and the developed optimization algorithms encouraged the researches concerned with optimization of gas distribution networks.

Osiadacz and Górecki [2] represented the optimization of gas networks for medium and low pressure networks using dynamic programming for sizing the pipe network diameters.

De Mélo Duarte et al. [18] proposed and applied a tabu search algorithm for the optimization of constrained gas distribution networks to find the least cost combination of diameters for the pipes, satisfying the constraints related to minimum pressure requirements and upstream pipe conditions.

Wu et al. [19] established a mathematical optimization model of the problem of minimizing the cost of pipelines incurred by driving the gas in a non-linear distribute network under steady-state assumptions. They presented a global approach to the optimization model.

Djebedjian et al. [20] proposed genetic algorithm in optimizing gas network distribution, the objective is to minimize the network cost by minimizing the pipe diameters of the network, with the constraints of minimum pressure at demand nodes and maximum velocity in pipes.

The previous literature review reveals that the majority of researches are focused on the optimization of transportation gas pipeline.

The main original contribution proposed in this paper is the application of the gradient algorithm of Todini and Pilati [21] for analyzing gas networks in linkage with the genetic algorithm (Holland [22] and Goldberg [23]) for optimization. The approach is applied to a case study of gas distribution, Moharram-Bek network.

2. PROPOSED STUDY

The main study was concerned with developing a computer program to simulate, analyze, solve and optimize low and medium pressure gas distribution networks.

2.1 Flow Equation

The pressure drop equations used in the design of gas pipelines have several versions, Osiadacz [1] and Coelho and Pinho [24]. The gas flow equations are divided into three categories corresponding to its pressure region: low-pressure, medium-pressure and high-pressure. In this study, the Pole's equation for medium pressure region (0-750 mbar gauge) was used, [1]:

$$p_1 - p_2 = \left(11.7\times10^3 \frac{L}{D^5}\right)Q^2 \qquad (1)$$

where the nodal pressure p is in mbar, D the diameter in mm, L the link length in m, and the flow rate Q in m^3/h.

2.2 Modeling

The method proposed by Todini and Pilati [21] is for water distribution networks. In this study, the application of this method was applied for gas networks and it constitutes of, [25]:

$$\mathbf{H}_{t+1} = -\left[\mathbf{A}_{21}(\mathbf{N}\mathbf{A}_{11})^{-1}\mathbf{A}_{12}\right]^{-1} \cdot \left[\mathbf{A}_{21}(\mathbf{N}\mathbf{A}_{11})^{-1}(\mathbf{A}_{11}\mathbf{Q}_t + \mathbf{A}_{10}\mathbf{H}_o) - (\mathbf{A}_{21}\mathbf{Q}_t - \mathbf{q}_o)\right] \qquad (2)$$

$$\mathbf{Q}_{t+1} = \left(\mathbf{I} - \mathbf{N}^{-1}\right)^{-1}\mathbf{Q}_t - \left[\mathbf{N}^{-1}\mathbf{A}_{11}^{-1}(\mathbf{A}_{12}\mathbf{H}_{t+1} + \mathbf{A}_{10}\mathbf{H}_0)\right] \qquad (3)$$

where:

- l: Number of links
- n: Number of demand junctions
- s: Number of source nodes
- $\mathbf{A}_{10}$: Source nodes links matrix; Dimension: (l x s)
- $\mathbf{A}_{11}$: Matrix of pressure losses; Dimension: (l x l)

$\mathbf{A}_{12}$: Demand junctions links matrix; Dimension: $(l \times n)$

$\mathbf{A}_{21}$: Transpose of $(\mathbf{A}_{12})$

$\mathbf{H}_{t+1}$: Unknown node pressure head matrix in the present iteration $t+1$; Dimension: $(n \times l)$

$\mathbf{H}_{0}$: Source nodes pressure head matrix, Dimension: $(s \times 1)$

$\mathbf{I}$: Identity matrix

$\mathbf{N}$: Matrix of flow rate exponent related to its flow-equation in its pressure range; Dimension: $(l \times l)$

$\mathbf{Q}_{t}$: Previous t iteration or initial flow rate matrix; Dimension: $(l \times 1)$

$\mathbf{Q}_{t+1}$: Unknown pipe flow matrix in the present iteration $t+1$; Dimension: $(l \times 1)$

$\mathbf{q}_{0}$: Flow rates demands at demand junctions; Dimension: $(n \times 1)$

The flow rates in pipes are to be assumed initially by:

$$Q_i = \frac{\pi}{4} D_i^2 v_i \qquad i = 1,\ldots,l \tag{4}$$

where $v_i = 1$ m/s for initiation

2.3 Data Structure

The relation between links and nodes is the most important issue to be established firmly. It's represented through the two matrices $\mathbf{A}_{12}$ and $\mathbf{A}_{10}$, so that $\mathbf{A}_{12}$ matrix represents the relationship between demand junctions (matrix rows), and all links (matrix columns), through (1, −1 and 0) numbers. It is "0" if there's no attachment between a link and a junction. It is "1" (or "−1") if the link is attached to a definite junction and is subjected to the junction direction (or the opposite direction).

After formulation, iteration starts until corrections in flow rates don't exceed a specified accuracy.

2.4 Optimization

Genetic Algorithms (GAs), (Holland [22] and Goldberg [23]), are adaptive heuristic search algorithm premised on the evolutionary ideas of natural selection and genetic. The basic concept of GAs is designed to simulate processes in natural system necessary for evolution, specifically those that follow the principles first laid down by Charles Darwin of survival of the fittest.

The GA approach does not require certain restrictive conditions as continuity and differentiability to the second order. The major advantages of genetic algorithms are their flexibility and robustness as a global search method.

Gas distribution network optimization searches the optimal pipe diameters in the network for a given layout and demand requirements to minimize the cost. The conservations of mass and energy, and the constraints are satisfied. The objective function is the cost and the constraints are the minimum nodal pressures and the maximum velocity in pipes to obtain as, [26].

Cost:

$$C_T = \sum_{i=1}^{l} c_i(D_i) \cdot L_i \tag{5}$$

Constraints:

$$D_{min} \le D_i \le D_{max} \quad i = 1,\ldots,l \tag{6}$$

$$v_i \le v_{max} \quad i = 1,\ldots,l \tag{7}$$

$$p_j \ge p_{min} \quad j = 1,\ldots,n \tag{8}$$

Objective function:

$$F = C_T + C_{Pv} + C_{Pp} \tag{9}$$

Penalty functions:

$$C_{Pv} = 0 \qquad \text{if } v_i \le v_{max}$$

$$C_{Pv} = \frac{C_T}{l} \sum_{i=1}^{l} (v_i^2 - v_{max}^2) \text{ if } v_i > v_{max} \tag{10}$$

$$C_{Pp} = 0 \qquad \text{if } p_j \ge p_{min}$$

$$C_{Pp} = \frac{C_T}{n} \sum_{j=1}^{n} (p_{min} - p_j) \text{ if } p_j < p_{min} \tag{11}$$

where:

$c_i(D_i)$: Cost of link i with diameter D_i

C_T: Total cost

C_{Pp}: Penalty cost for nodal pressure

C_{Pv}: Penalty cost for velocity

D_i: Diameter of Link i

D_{max}: Maximum diameter

D_{min}: Minimum diameter

F: Objective function

L_i: Length of link i

p_j: Actual gas pressure at junction j

p_{min}: Minimum gas pressure at junctions (18 mbar)

v_i: Actual gas velocity in link i

v_{max}: Maximum gas velocity in links (10 m/s)

2.5 Code Arrangement

The code was written in language C/C++ and called ***GAGAGas.net*** software, stands for (Gradient Algorithm Genetic Algorithm Gas network). The developed code passes through three main stages:

(a) Network graph analysis,
(b) Network analysis and simulation, and
(c) Network optimization.

The network graph includes the nodes and links identification codes and correctness verification of given input data of network. Network analysis and simulation, in which the simulation of pressure and flow rates through the network, were formulated through gradient algorithm, Todini and Pilati [21] and using Equations (2) and (3). In the two previous stages many programmed functions were borrowed from EPANET 2.0 (Rossman [27]) and "*Numerical Recipes in C*" (Press et al. [28]). Network optimization applied the Real-Coded Genetic Algorithm (Deb [29]) to search randomly in optimized space and then converge to better solutions.

Figure 1 shows the simulation and analysis engine flow diagram, it contains the simulation, arranging matrices and network analysis. Figure 2 illustrates the optimization engine and includes the initialization, selection procedure, new generation, crossover, mutation, fitness and reporting.

A brief description of using GA in this study is as follows:

1. ***Initiation of the first generation.*** The initial generation is the existing design denoted by the user to be optimized.
2. ***Simulation.*** Simulation is then performed for the available network data so that getting the output data of velocities in links and pressures at nodes.
3. ***Costing.*** Evaluating the cost depends on two main points; the first is the actual cost of the available piping arrangement given as size-cost table. The second is to evaluate the penalties that happened due to the deviation away from constraints by velocities in links or pressures at nodes.
4. ***Fitness.*** The fitness of the coded string is taken as some function of the total network cost. For each proposed pipe network in the current population, it can be computed as the inverse or the negative value of the total network cost.
5. ***Selection.*** In this study GA uses *Tournament* technique for selection from the population the best individuals to pass through.
6. ***Crossover and mutation.*** Crossover happens to the most of the selected generation in probability of 0.6 as some of good individuals may pass without making any operations on them. Very low mutation probability of about 0.04 is used.
7. ***Successive generations.*** Now there is a new generation to start over from the simulation step. This procedure is continued till the total number of generations, is met.

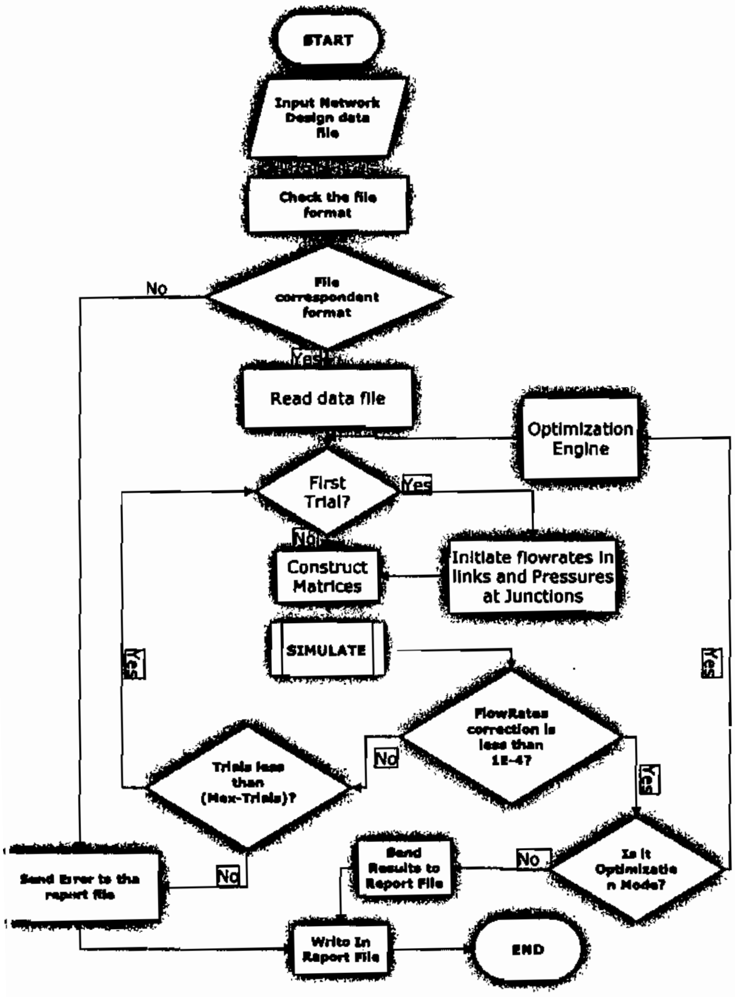

Fig. 1. Flow diagram for the simulation and analysis engine

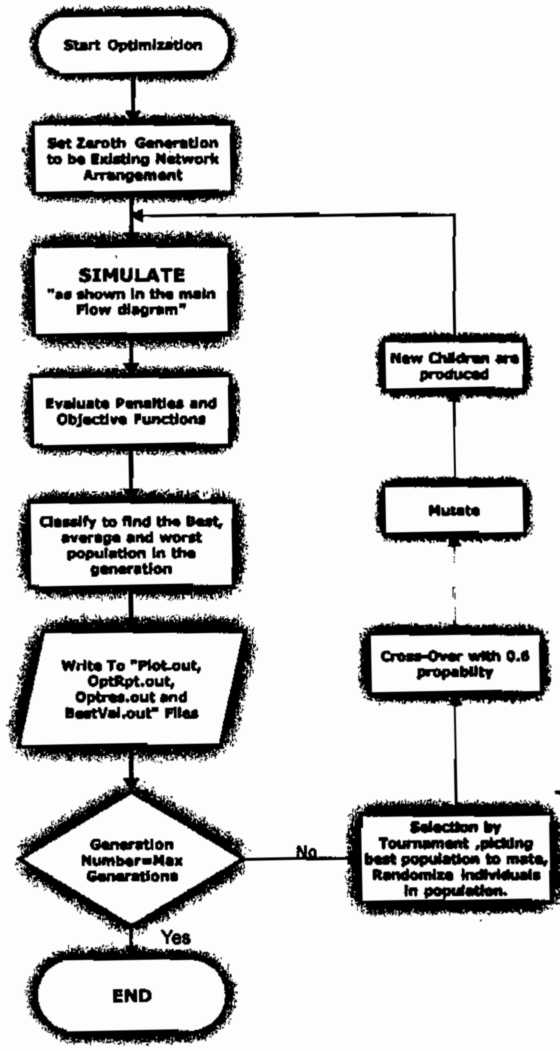

Fig. 2. Flow diagram for the optimization engine

3. CASE STUDY

An actual gas network has been selected to apply the developed code to evaluate the design of the network and to test its capabilities in a real and large gas distribution network. The selected gas distribution network is part of Moharram-Bek low-pressure distribution gas network (Alexandria, Egypt). It comprises 125 junctions, 137 branches and two sources of 100 mbar in pressure, Figure 3. The main case study and the parameters of the genetic algorithm are given in Table 1. This case study is real case study in Egypt. The data of nodes (demand or branch nodes) and source nodes are given in Tables A1 and A2, respectively, in the Appendix. For source node, the pressure of the network is provided, while for demand nodes the demands flow rates to the nodes are provided and the branching point have zero demand flow rate. The total piping length is 25210 m, whereas the total demands is 1282.8 m^3/h. The data of branches are given in Table A3.

The gas network constraints were: minimum gas pressure at junction was 18 mbar and maximum gas velocity in link was 10 m/s. The Pole's equation as pressure losses formula was used in the low-pressure region. The cost of pipe was estimated by the relationship, [2]: $C = 2.05\,L\,D^{1.3}$ in which C is the cost in Zlotys (US$ = 2.36 Zloty, [2]), L the length in meters and D the diameter in inches.

They used the continuous optimization method that supposes that any size of diameter is possible; therefore the resulted set of diameters is corrected to closest available diameter sizes. In this study, the available pipe diameters mentioned in [2] are used and the corresponding costs per meter length are mentioned in Table A4.

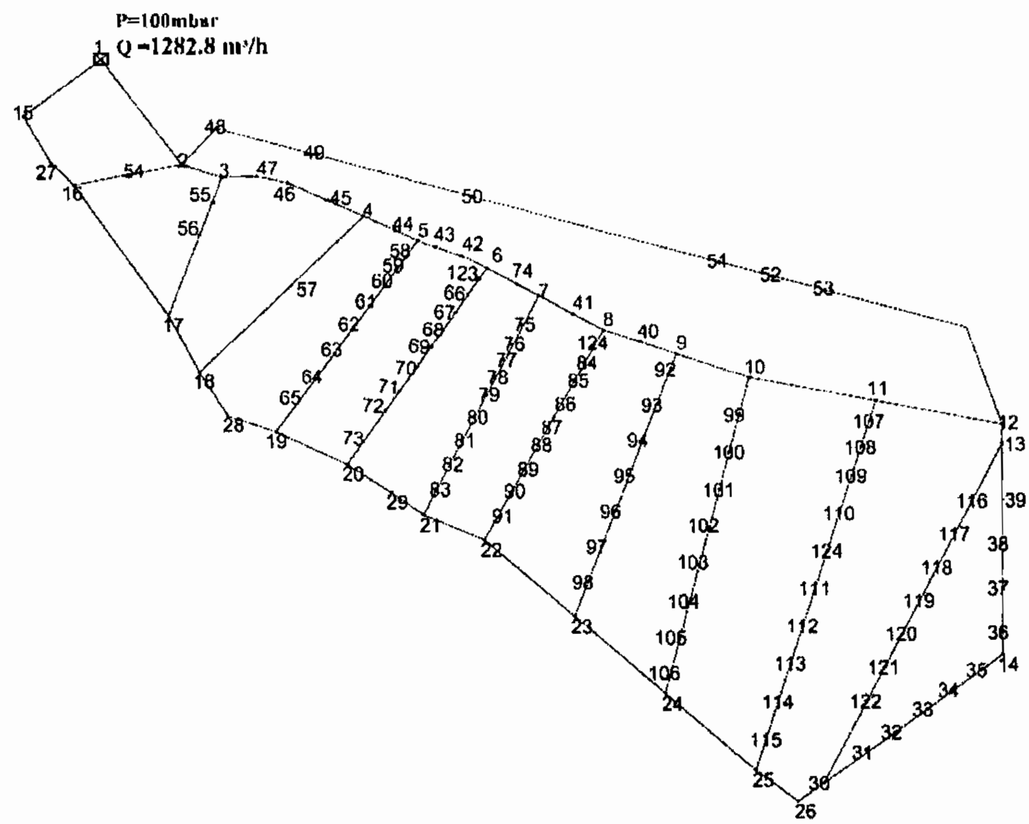

Fig. 3. Moharram-Bek low-pressure gas distribution network layout

Table 1. Case study and genetic algorithm data

Case Study		Accuracy	0.0001 m^3/hr
Pressure Range	Low Pressure	Maximum No. of Trials	40
Number of Sources	1	**Constraints**	
Number of Branches	137	Maximum Branch Velocity	10 m/s
Number of Junctions	125	Minimum Node Pressure	18 mbar
Source Pressure	100 mbar	**Genetic Algorithm**	
Fluid	Natural Gas*	Population Size	50
Temperature	Ambient (25°C)	Total No. of Generations	500
Simulation		Crossover Probability	0.8
Pressure Losses Formula	Pole's Equation	Mutation Probability (Real)	0.06
Gas Network Analysis	Gradient Algorithm	Number of Real-Coded Variables	39

* *As it is rich Methane content, the natural gas assumed to be Methane.*

4. RESULTS AND DISCUSSION

The ***GAGAGas.net*** software released the network analysis for the already designed network, and the optimization data for the network. The simulation and optimization analyses are discussed in the following sections.

4.1 Simulation Analysis

The results of simulation analysis (i.e. before optimization) are represented in Figures 4-6. Figure 6 shows that many links' velocities are very low which indicates using larger pipe sizes than suitable and some few branch members are violating the constraint of maximum velocity, so optimizing this network sizing was required.

4.2 Optimization Analysis

The optimization action was marking an outstanding role in reducing the network cost. The comparison between flow velocities before and after optimization is given in Table A5.

Figure 4 displays the comparison between the branch sizes before and after optimization. The objective function of the optimization was the cost which depends on the link diameter; i.e. the aim of optimization was decreasing the diameter to minimize the cost. The optimal set of diameters has generally small diameters compared to the original ones.

Figure 5 represents the nodal pressures before and after optimization and the minimum required nodal pressures. For the designed network, all the pressures have high pressures above the nodal pressure constraint as the designed branch diameters are big and accordingly, the pressure losses are small. The small link diameters from optimization cause the increase in pressure losses and decrease the nodal pressure, Figure 5.

Figure 6 shows the flow velocities in each link in the designed and optimum network. Also, the minimum velocity constraint is shown. Because of the change in links-size set resulted from optimization, the flow velocities in all links were increased but they were below the maximum velocity constraint.

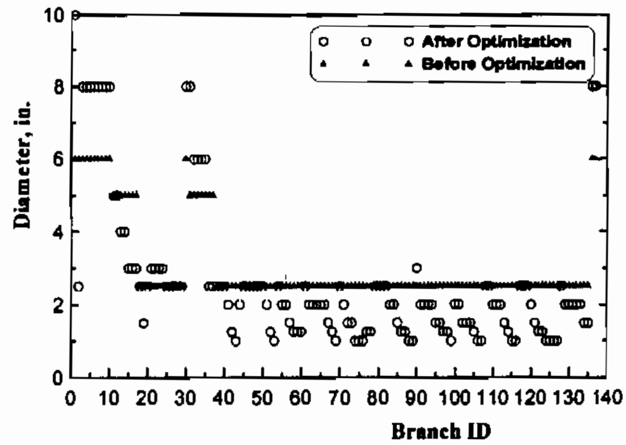

Fig. 4. Pipes diameters before and after optimization for the case study

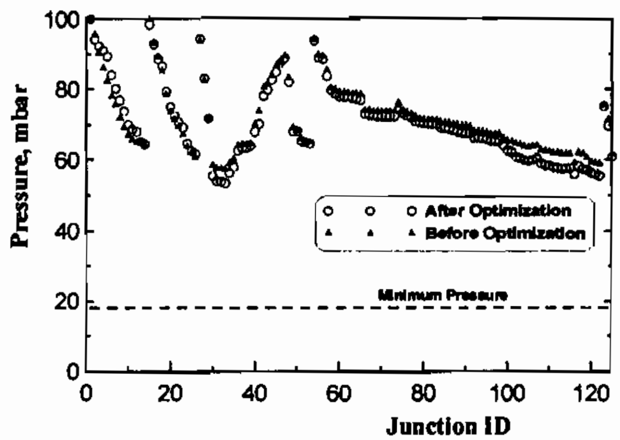

Fig. 5. Nodal pressures at nodes before and after optimization for the case study

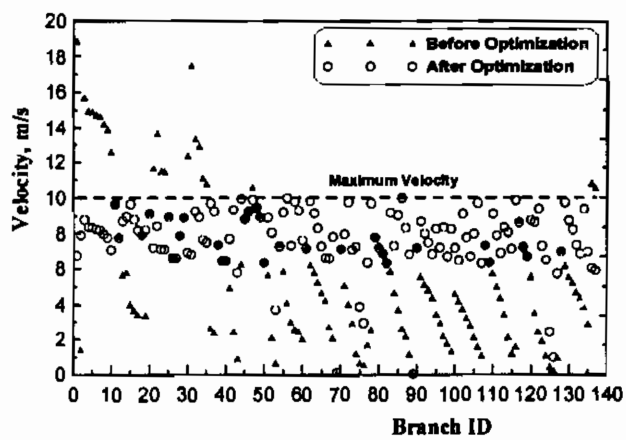

Fig. 6. Velocities in pipes before and after optimization for the case study

As can be seen from Figures 5 and 6, all the constraints were satisfied with this optimal gas distribution network.

Figure 7 shows the best, average, and worst fitnesses for each fifth increasing generation for clarity. It should be noted that the best fitness is always feasible solution but for the average and worst solutions, they may be feasible and may be not. The code doesn't deviate between feasible and infeasible solution automatically.

Figure 8 compares the cost of the original network design and the network generated from the present study after optimization. This network containing 137 pipes and with 15 available commercial pipe sizes has a total solution space of 15^{137} different network designs. The GA optimization technique found the best solution $ 76,744.772 at generation no. 274. The original (design) cost is $ 97,212.6; therefore the optimal cost is approximately 78.95% of the original cost.

Figure 9 represents the difference between the optimal cost and original cost of each pipe. As the cost is dependent on pipe length and diameter, Fig. 4, there are some pipes with equal original and optimal costs and others with optimal costs greater or lesser than the original ones. The overall average change between the original and optimal network costs for each pipe is $ 149.4. The most critical pipe that affects the overall pipe network cost is Pipe number (2); its length is 1000 m and has an original diameter of 6 inch and optimal diameter of 2.5 inch.

Figure 10 shows the total pipe length of the used pipe diameters over the whole network for the optimal and original networks. It gives an indication about how the wide range of commercial pipe diameters are used in optimal solution compared to the original one. Even the optimal solution uses higher pipe diameters reaching the diameter of 10 inch whereas the original maximum diameter was 6 inch; the network cost of the optimal solution is less than the original one.

The optimization run time was 25 minutes and obtained by a computer with Intel Pentium 4 (2 GHz) processor and 256 MB of Ram. Generally, there is strong computing time saving compared to those obtained with other optimization techniques.

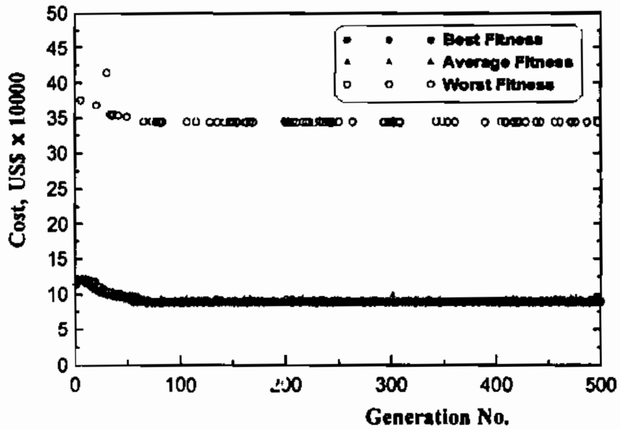

Fig. 7. Fitness of all solutions; best, average and worst fitnesses for the case study

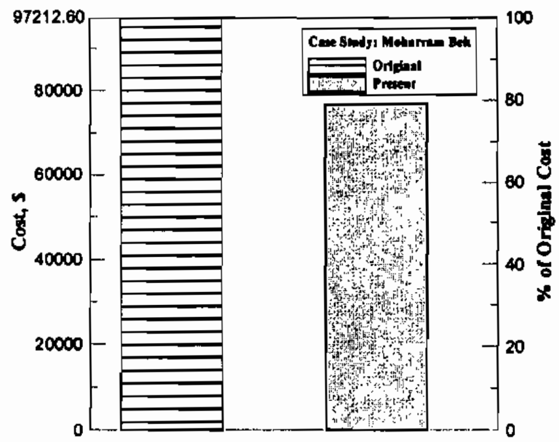

Fig. 8. Comparison between Moharram-Bek network original design and the present study generated design

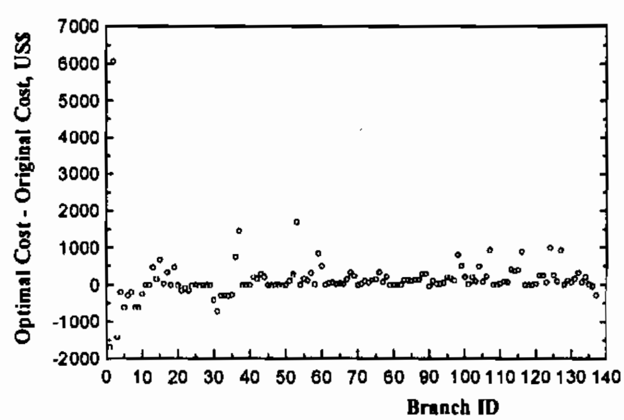

Fig. 9. Difference between optimal cost and original cost of each pipe

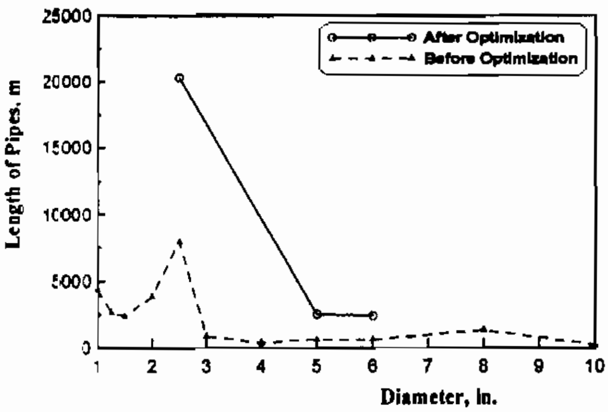

Fig. 10. Length of pipes for each pipe size for original network and optimal network

5. CONCLUSIONS

The optimization of a large-scale gas distribution network is a complex problem. The utilization of genetic algorithms for optimization with the gradient algorithm for simulation has been presented in the present paper. A numerical code for optimal design and cost evaluation of a gas distribution network was developed.

The study presents the optimization of Moharrm-Bek network to determine the optimal set of pipes diameters in order to minimize the invested cost. The optimization of gas distribution network is computationally complex as the constraints of maximum velocity in links and minimum required nodal pressure should be fulfilled. The optimal diameters of pipes were chosen from commercial size diameters. The results show that the genetic algorithm is a very efficient, robust, and flexible algorithm to reach solutions.

For the case study of Moharram-Bek gas network (Alexandria, Egypt), the obtained optimal cost is \$ 76,744.772 which is approximately 78.91% of the original cost \$ 97,212.6. Therefore, the approach shows attractive ability to handle the large-scale gas distribution network optimization problem efficiently.

REFFERENCES

[1] **Osiadacz, A.J.,** *Simulation and Analysis of Gas Pipeline Networks*, E. & F.N. Spon Ltd., London, 1987.

[2] **Osiadacz, A.J., and Górecki, M.,** "Optimization of Pipe Sizes for Distribution Gas Network Design," *PSIG 27th Annual Meeting*, Albuquerque, New Mexico, October 18-20, 1995. http://www.psig.org/papers/1990/9511.pdf

[3] **Herrán-González, A., De La Cruz, J.M., De Andrés-Toro, B., and Risco-Martín, J.L.,** "Modeling and Simulation of a Gas Distribution Pipeline Network," *Applied Mathematical Modeling*, Vol. 33, Issue 3, March 2009, pp. 1584-1600.

[4] **Osiadacz, A.J.,** "Dynamic Optimization of High Pressure Gas Networks using Hierarchical Systems Theory," *PSIG 26th Annual Meeting*, San Diego, California, October 13-14, 1994. http://www.psig.org/papers/1990/9408.pdf

[5] **Wu, S., Ríos-Mercado, R.Z., Boyd, E.A., and Scott, L.R.,** "Model Relaxations for the Fuel Cost Minimization of Steady-State Gas Pipelines Networks," *Mathematical and Computer Modelling*, Vol. 31, Issues 2-3, January-February 2000, pp. 197-220.

[6] **Larson, R.E., and Wong, P.J.,** "Optimization of Natural Gas System via Dynamic Programming," *Industrial and Engineering Chemistry*, Vol. AC 12 (5), 1968, pp. 475-481.

[7] **Martch, H.B., and McCall, N.J.,** "Optimization of the Design and Operation of Natural Gas Pipeline Systems," Paper No. SPE 4006, *Society of Petroleum Engineers of AIME*, 1972.

[8] **O'Neill, R.P., Williard, M., Wilkins, B., and Pike, R.,** "A Mathematical Programming Model for Allocation of Natural Gas," *Operations Research*, Vol. 27, No 5, 1979, pp. 857-873.

[9] **Olorunniwo, F.O., and Jensen, P.A.,** "Optimal Capacity Expansion Policy for Natural Gas Transmission Networks – A Decomposition Approach," *Engineering Optimization*, Vol. 6, 1982, pp. 13-30.

[10] **Edgar, T.F., and Himmelblau, D.M.,** *Optimization of Chemical Processes*. McGraw Hill Book Company, New York. 1988.

[11] **De Wolf, D., and Smeers, Y.,** "Optimal Dimensioning of Pipe Networks with Application to Gas Transmission Network," *Operations Research*, Vol. 44, No. 4, 1996, pp. 596-608. http://gremars.univ-lille3.fr/~dewolf/Optdim.pdf

[12] **De Wolf, D., and Smeers, Y.,** "The Gas Transmission Problem Solved by an Extension of the Simplex Algorithm," *Management Sciences*, Vol. 46, No 11, Nov. 2000, pp. 1454-1465.

[13] **Ríos-Mercado, R.Z., Wu, S., Scout, L.R., and Boyd, E.A.,** "A Reduction Technique for Natural Gas Transmission Network Optimization Problems," *Annals of Operations Research*, Vol. 117, 2002, pp. 217-234.

[14] **Babu, B.V., Angira, R., Chakole, P.G., and Syed Mubeen, J.H.,** "Optimal Design of Gas Transmission Network Using Differential Evolution," *Proceedings of The Second International Conference on Computational Intelligence, Robotics, and Autonomous Systems* (CIRAS-2003), Singapore, December 15-18, 2003, PS0402, pp. 01-07. http://discovery.bitspilani.ac.in/discipline/chemical/BVb/RevisedBabRakPalMub20CIRAS-2003.pdf

[15] **Pietrasz, S., Antunes, M., and Cornibert, L.,** "The Problem of Reinforcing Regional Gas Transmission Networks: A Performance Study of Three Optimization Methods," *EngOpt 2008 - International Conference on Engineering Optimization*, Rio de Janeiro, Brazil, 1-5 June 2008, pp. 1-10.

[16] **André, J., Bonnans, F., and Cornibert, L.,** "Optimization of Capacity Expansion Planning for Gas Transportation Networks," *European Journal of Operational Research*, Vol. 197, Issue 3, 2009, pp. 1019-1027.

[17] **Chebouba, A., Yalaoui, F., Smati, A., Amodeo, L., Younsi, K., and Tairi, A.,** "Optimization of Natural Gas Pipeline Transportation using Ant Colony Optimization," *Computers & Operations Research*, Vol. 36, Issue 6, 2009, pp. 1916-1923.

[18] **de Mélo Duarte, H., Goldbarg, E.F.G., and Goldbarg, M.C.,** "A Tabu Search Algorithm for Optimization of Gas Distribution Networks," *Lecture Notes in Computer Science, Evolutionary Computation in Combinatorial Optimization*, Vol. 3906, 2006, pp. 37-48.

[19] **Wu, Y., Lai, K.K., and Liu, Y.,** "Deterministic Global Optimization Approach to Steady-State Distribution Gas Pipeline Networks," *Optimization and Engineering*, Vol. 8, No. 3, 2007, pp. 259-275.

[20] **Djebedjian, B., El-Naggar, M. and Shahin, I.,** "Gas Distribution Network Optimization by Genetic Algorithm," *Ninth International Congress of Fluid Dynamics & Propulsion*, December 18-21, 2008, Alexandria, Egypt.

[21] **Todini, E., and Pilati, S.,** "A Gradient Method for the Analysis of Pipe Networks," *Proceedings of the International Conference on Computer Applications for Water Supply and Distribution*, Leicester Polytechnic, Leicester, U.K., September 1987.

[22] **Holland, J.H.,** *Adaptation in Natural and Artificial System*, Ann Arbor, The University of Michigan Press, 1975.

[23] **Goldberg, D.E.,** *Genetic Algorithms in Search, Optimization and Machine Learning*, Addison-Wesley Reading, Mass., 1989.

[24] **Coelho, P.M., and Pinho, C.,** "Considerations About Equations for Steady State Flow in Natural Gas Pipelines," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, Vol. XXIX, No. 3, July-September 2007, pp. 262-273.

[25] **Bhave, P.R., and Gupta, R.,** *Analysis of Water Distribution Networks*, Alpha Science International Ltd., Oxford, U.K., 2006.

[26] **Djebedjian, B., Yaseen, A., and Abou Rayan, M.,** "A New Adaptive Method for Constrained Genetic Algorithm and its Application to Water Distribution Systems," *International Pipeline Conference and Exposition 2006* (IPC2006), September 25-29, 2006, Calgary, Alberta, Canada, Paper IPC00-10235.

[27] **Rossman, L.A.,** *EPANET 2 Users Manual*, Environmental Protection Agency, 2000. http://www.epa.gov/nrmrl/wswrd/dw/epanet/EN2manual.pdf

[28] **Press, W.H., Teukolsky, S.A., Vetterling, W.T., and Flannery, B.P.,** *Numerical Recipes in C: the Art of Scientific Computing*, Second Edition, Cambridge University Press, 1992.

[29] **Deb, K., 2001** http://www.iitk.ac.in/kangal/codes.shtml

APPENDIX A: CASE STUDY OF MOHARRAM-BEK DATA AND RESULTS

Table A1. Nodes data for "Case study of Moharram-Bek"

Junction ID	Demand (m^3/h)	Junction ID	Demand (m^3/h)	Junction ID	Demand (m^3/h)
1	Source	43	15.6	85	3.6
2	0.0	44	21.6	86	4.8
3	0.0	45	6.0	87	10.8
4	0.0	46	9.6	88	4.8
5	0.0	47	4.8	89	8.4
6	0.0	48	12.0	90	4.8
7	0.0	49	6.0	91	4.8
8	0.0	50	28.8	92	4.8
9	0.0	51	8.4	93	4.8
10	0.0	52	39.6	94	6.0
11	0.0	53	16.8	95	4.8
12	0.0	54	16.8	96	7.2
13	0.0	55	12.0	97	6.0
14	0.0	56	4.8	98	6.0
15	0.0	57	4.8	99	10.8
16	0.0	58	10.8	100	7.2
17	0.0	59	4.8	101	8.4
18	0.0	60	6.0	102	7.2
19	0.0	61	7.2	103	10.8
20	0.0	62	4.8	104	14.4
21	0.0	63	16.8	105	36.0
22	0.0	64	7.2	106	4.8
23	0.0	65	22.8	107	15.6
24	0.0	66	24.0	108	6.0
25	0.0	67	12.0	109	13.2
26	0.0	68	12.0	110	22.8
27	51.6	69	19.2	111	6.0
28	24.0	70	6.0	112	9.6
29	26.4	71	12.0	113	7.2
30	49.2	72	13.2	114	6.0
31	27.6	73	9.6	115	8.4
32	16.8	74	14.4	116	9.6
33	80.4	75	3.6	117	7.2
34	28.8	76	6.0	118	3.6
35	4.8	77	6.0	119	6.0
36	12.0	78	13.2	120	3.6
37	32.4	79	10.8	121	6.0
38	10.8	80	12.0	122	10.8
39	15.6	81	4.8	123	7.2
40	12.0	82	12.0	124	19.2
41	19.2	83	12.0	125	12.0
42	14.4	84	4.8		

*Source node

Table A2. Source nodes for the case study

Source ID	Pressure (mbar)
1	100

Table A3. Branches data for "Case study of Moharram-Bek"

Branch ID	Start Node	End Node	Length (m)	Diameter (in.)	Branch ID	Start Node	End Node	Length (m)	Diameter (in.)
1	1	2	200.0	6.0	54	2	54	150.0	2.5
2	1	15	1000.0	6.0	55	54	16	230.0	2.5
3	2	3	350.0	6.0	56	3	55	170.0	2.5
4	3	47	50.0	6.0	57	55	56	230.0	2.5
5	46	47	150.0	6.0	58	56	17	10.0	2.5
6	45	46	70.0	6.0	59	4	57	500.0	2.5
7	45	4	50.0	6.0	60	18	57	300.0	2.5
8	4	44	150.0	6.0	61	5	58	10.0	2.5
9	5	44	150.0	6.0	62	58	59	80.0	2.5
10	5	43	60.0	6.0	63	59	60	100.0	2.5
11	9	10	300.0	5.0	64	60	61	40.0	2.5
12	10	11	300.0	5.0	65	61	62	70.0	2.5
13	11	12	270.0	5.0	66	62	63	40.0	2.5
14	12	13	90.0	5.0	67	63	64	120.0	2.5
15	13	39	200.0	5.0	68	64	65	200.0	2.5
16	38	39	10.0	5.0	69	65	19	120.0	2.5
17	38	37	100.0	5.0	70	123	66	220.0	2.5
18	15	27	650.0	2.5	71	66	67	40.0	2.5
19	27	16	350.0	2.5	72	67	68	80.0	2.5
20	16	17	320.0	2.5	73	68	69	50.0	2.5
21	17	18	200.0	2.5	74	69	70	70.0	2.5
22	18	28	100.0	2.5	75	70	71	80.0	2.5
23	28	19	200.0	2.5	76	71	72	170.0	2.5
24	19	20	10.0	2.5	77	72	73	50.0	2.5
25	20	29	150.0	2.5	78	73	20	130.0	2.5
26	29	21	120.0	2.5	79	6	123	10.0	2.5
27	21	22	260.0	2.5	80	7	75	200.0	2.5
28	22	23	10.0	2.5	81	75	76	80.0	2.5
29	23	24	280.0	2.5	82	76	77	100.0	2.5
30	43	42	100.0	6.0	83	77	78	180.0	2.5
31	42	6	120.0	5.0	84	78	79	180.0	2.5
32	7	41	150.0	5.0	85	79	80	80.0	2.5
33	41	8	150.0	5.0	86	80	81	80.0	2.5
34	8	40	160.0	5.0	87	81	82	80.0	2.5
35	40	9	140.0	5.0	88	82	83	150.0	2.5
36	36	37	180.0	5.0	89	83	21	150.0	2.5
37	36	14	350.0	5.0	90	8	124	50.0	2.5
38	24	25	10.0	2.5	91	124	84	150.0	2.5
39	25	26	200.0	2.5	92	84	85	40.0	2.5
40	26	30	360.0	2.5	93	85	86	40.0	2.5
41	30	31	290.0	2.5	94	86	87	80.0	2.5
42	31	32	100.0	2.5	95	87	88	150.0	2.5
43	32	33	150.0	2.5	96	88	89	130.0	2.5
44	33	34	300.0	2.5	97	89	90	70.0	2.5
45	34	35	100.0	2.5	98	90	91	480.0	2.5
46	35	14	300.0	2.5	99	91	22	260.0	2.5
47	2	48	750.0	2.5	100	9	92	300.0	2.5
48	48	49	1050.0	2.5	101	92	93	30.0	2.5
49	49	50	80.0	2.5	102	93	94	150.0	2.5
50	50	51	400.0	2.5	103	94	95	70.0	2.5
51	51	52	150.0	2.5	104	95	96	360.0	2.5
52	52	53	170.0	2.5	105	96	97	60.0	2.5
53	12	53	850.0	2.5	106	97	98	120.0	2.5

Table A3 (Continued)

Branch ID	Start Node	End Node	Length (m)	Diameter (in.)
107	98	23	470.0	2.5
108	10	99	100.0	2.5
109	99	100	150.0	2.5
110	100	101	50.0	2.5
111	101	102	120.0	2.5
112	102	103	110.0	2.5
113	103	104	300.0	2.5
114	104	105	220.0	2.5
115	105	106	200.0	2.5
116	106	24	450.0	2.5
117	11	107	150.0	2.5
118	107	108	150.0	2.5
119	108	109	50.0	2.5
120	109	110	30.0	2.5
121	110	125	180.0	2.5
122	125	111	150.0	2.5
123	111	112	40.0	2.5
124	112	113	500.0	2.5
125	113	114	130.0	2.5
126	114	115	50.0	2.5
127	115	25	470.0	2.5
128	13	116	10.0	2.5
129	116	117	160.0	2.5
130	117	118	100.0	2.5
131	118	119	230.0	2.5
132	119	120	450.0	2.5
133	120	121	100.0	2.5
134	121	122	150.0	2.5
135	122	30	10.0	2.5
136	6	74	10.0	6.0
137	7	74	70.0	6.0

Table A4. Piping cost per 1 meter length

D (mm)	D (inch)	Cost (Zloty) / L (m) = $2.05\ D^{1.3}$	D (mm)	D (inch)	Cost (Zloty) / L (m) = $2.05\ D^{1.3}$
12.5	0.50	0.8326	100	4.00	12.4289
18.75	0.75	1.4104	125	5.00	16.6117
25	1.00	2.0500	150	6.00	21.0548
31.25	1.25	2.7399	200	8.00	30.6035
37.5	1.50	3.4727	250	10.00	40.9029
50	2.00	5.0477	300	12.00	51.8429
62.5	2.50	6.7465	400	16.00	75.3546
75	3.00	8.5509			

Table A5. Optimized versus existing simulation for "Case study of Moharram-Bek"

Branch ID	Design		Optimization		ΔD* (in.)
	Diameter (in.)	Velocity (m/s)	Diameter (in.)	Velocity (m/s)	
1	6	18.77	10	6.76	-4
2	6	1.39	2.5	7.91	3.5
3	6	15.63	8	8.79	-2
4	6	14.92	8	8.39	-2
5	6	14.84	8	8.35	-2
6	6	14.69	8	8.26	-2
7	6	14.60	8	8.21	-2
8	6	14.17	8	7.97	-2
9	6	13.83	8	7.78	-2
10	6	12.57	8	7.07	-2
11	5	9.63	5	9.63	0
12	5	7.77	5	7.77	0
13	5	5.58	4	8.71	1
14	5	5.73	4	8.95	1
15	5	3.95	3	9.65	2
16	5	3.60	3	8.79	2
17	5	3.35	3	8.19	2
18	2.5	7.91	2.5	7.91	0
19	2.5	3.31	1.5	8.21	1
20	2.5	9.11	2.5	9.11	0
21	2.5	11.25	3	7.21	-0.5
22	2.5	13.60	3	8.43	-0.5
23	2.5	11.46	3	7.11	-0.5
24	2.5	11.44	3	7.10	-0.5
25	2.5	8.95	2.5	8.95	0
26	2.5	6.60	2.5	6.60	0
27	2.5	6.60	2.5	6.60	0
28	2.5	7.90	2.5	7.90	0
29	2.5	8.89	2.5	8.89	0
30	6	12.33	8	6.93	-2
31	5	17.43	8	6.81	-3
32	5	13.30	6	9.24	-1
33	5	12.87	6	8.94	-1
34	5	11.05	6	7.67	-1
35	5	10.77	6	7.48	-1
36	5	2.62	2.5	9.87	2.5
37	5	2.35	2.5	9.40	2.5
38	2.5	7.34	2.5	7.34	0
39	2.5	6.44	2.5	6.44	0
40	2.5	6.44	2.5	6.44	0
41	2.5	4.87	2	7.61	0.5
42	2.5	2.41	1.25	9.64	1.25
43	2.5	0.91	1	5.69	1.5
44	2.5	6.25	2	9.77	0.5
45	2.5	8.82	2.5	8.82	0
46	2.5	9.25	2.5	9.25	0
47	2.5	10.53	2.5	9.74	0

* $\Delta D = D_{Design} - D_{Optimal}$

Table A5 (Continued)

Branch ID	Design		Optimization		ΔD* (in.)
	Diameter (in.)	Velocity (m/s)	Diameter (in.)	Velocity (m/s)	
48	2.5	9.46	2.5	9.46	0
49	2.5	8.92	2.5	8.92	0
50	2.5	6.36	2.5	6.36	0
51	2.5	5.61	2	8.77	0.5
52	2.5	2.08	1.25	8.32	1.25
53	2.5	0.58	1	3.63	1.5
54	2.5	7.29	2.5	7.29	0
55	2.5	5.80	2	9.06	0.5
56	2.5	4.02	2	6.28	0.5
57	2.5	2.95	1.5	8.19	1
58	2.5	2.52	1.25	9.98	1.25
59	2.5	2.40	1.25	9.60	1.25
60	2.5	1.97	1.25	7.88	1.25
61	2.5	7.15	2.5	7.15	0
62	2.5	6.19	2	9.67	0.5
63	2.5	5.76	2	9.00	0.5
64	2.5	5.22	2	8.16	0.5
65	2.5	4.58	2	7.16	0.5
66	2.5	4.15	2	6.48	0.5
67	2.5	2.66	1.5	7.39	1
68	2.5	2.02	1.25	8.08	1.25
69	2.5	0.02	1	0.13	1.5
70	2.5	7.13	2.5	7.64	0
71	2.5	4.99	2	7.80	0.5
72	2.5	3.92	1.5	9.74	1
73	2.5	2.85	1.5	7.92	1
74	2.5	1.14	1	7.13	1.5
75	2.5	0.61	1	3.81	1.5
76	2.5	0.46	1	2.88	1.5
77	2.5	1.64	1.25	6.56	1.25
78	2.5	2.49	1.25	9.96	1.25
79	2.5	7.77	2.5	8.01	0
80	2.5	7.17	2.5	8.05	0
81	2.5	6.85	2.5	7.12	0
82	2.5	6.31	2.5	6.82	0
83	2.5	5.78	2	9.03	0.5
84	2.5	4.60	2	7.19	0.5
85	2.5	3.64	1.5	9.94	1
86	2.5	2.57	1.25	9.89	1.25
87	2.5	2.14	1.25	8.56	1.25
88	2.5	1.07	1	6.69	1.5
89	2.5	0.01	1	0.06	1.5
90	2.5	7.18	3	4.99	-0.5
91	2.5	5.47	2	8.55	0.5
92	2.5	5.04	2	7.88	0.5
93	2.5	4.72	2	7.38	0.5

Table A5 (Continued)

Branch ID	Design		Optimization		ΔD* (in.)
	Diameter (in.)	Velocity (m/s)	Diameter (in.)	Velocity (m/s)	
94	2.5	4.29	2	6.70	0.5
95	2.5	3.33	1.5	9.25	1
96	2.5	2.90	1.5	8.06	1
97	2.5	2.15	1.25	8.60	1.25
98	2.5	1.73	1.25	6.92	1.25
99	2.5	1.30	1	8.13	1.5
100	2.5	4.52	2	7.06	0.5
101	2.5	4.09	2	6.39	0.5
102	2.5	3.67	1.5	9.99	1
103	2.5	3.13	1.5	8.69	1
104	2.5	2.70	1.5	7.50	1
105	2.5	2.06	1.25	8.24	1.25
106	2.5	1.53	1	9.56	1.5
107	2.5	0.99	1	6.19	1.5
108	2.5	7.32	2.5	7.32	0
109	2.5	6.36	2.5	6.36	0
110	2.5	5.72	2	8.94	0.5
111	2.5	4.97	2	7.77	0.5
112	2.5	4.33	2	6.77	0.5
113	2.5	3.37	1.5	9.36	1
114	2.5	2.08	1.25	8.32	1.25
115	2.5	1.12	1	7.00	1.5
116	2.5	1.55	1	9.69	1.5
117	2.5	8.61	2.5	8.61	0
118	2.5	7.22	2.5	7.43	0
119	2.5	6.69	2.5	6.43	0
120	2.5	5.51	2	8.61	0.5
121	2.5	3.48	1.5	9.67	1
122	2.5	2.41	1.25	9.64	1.25
123	2.5	1.88	1.25	7.52	1.25
124	2.5	1.02	1	6.38	1.5
125	2.5	0.38	1	2.38	1.5
126	2.5	0.15	1	0.94	1.5
127	2.5	0.90	1	5.63	1.5
128	2.5	6.98	2.5	7.13	0
129	2.5	6.13	2	9.58	0.5
130	2.5	5.49	2	8.58	0.5
131	2.5	5.17	2	8.08	0.5
132	2.5	4.63	2	7.23	0.5
133	2.5	4.31	2	6.73	0.5
134	2.5	3.77	1.5	9.87	1
135	2.5	2.81	1.5	7.81	1
136	6.0	10.73	8	6.04	-2
137	6.0	10.50	8	5.91	-2

Cost (Design) = $ 97,212.6
Cost (Present Study) = $ 76,744.772
Profit = $ 20467.828