Optimal Design and Operation of Egyptian Gas-Transmission Pipelines

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Summary
Natural gas is increasingly being used as an energy source. Natural gas transmission pipelines transport large quantities of natural gas across long distances. They operate at high pressures and use a series of compressor stations at frequent intervals along the pipeline (more than 60 miles) to move the gas over long distances.

The objective function is given by a nonlinear function of flow rates and pressures. The optimization problem has been solved with a number of decision variables and the number of constraints to find the optimal design variables and operations of transmission pipelines over flat terrain. The objective function includes installation cost of pipelines, compressor stations, fuel consumption in compressor stations, maintenance, labor, and supervision. The software program LINGO (LINDO 1997) is used to obtain the solution procedure for optimal design and operation of gas-transmission pipelines.

Introduction
As natural gas pipeline systems have grown larger and more complex, the importance of optimization of design and operation of pipelines has increased. The investment costs and operation expenses of pipeline networks are so large that even small improvements in design and operation conditions can lead to substantial saving in capital and operating cost. Optimization of natural gas pipelines is often used to determine the optimum system variables in order to minimize the total cost.

Bolkan et al (1992) show an algorithm for solving the multivariable, interconnected pipeline-optimization problem with several appropriate constraints. Aside from optimizing the design of the pipeline network, the algorithm could also be used for optimizing the operating conditions.

Mantri et al. (1986) show that a computer program could minimize the operating costs of natural gas pipelines through minimization of fuel consumption at compressor stations in order to minimize the total cost.

Dobersek and Goricanec (2009) and Goricanec and Krope (2003) show the optimization of pipe network with hot water. The mathematical model, consisting of the nonlinear objective function and a system of nonlinear equations for the hydraulics limitations, is developed. On its basis, the computer program for determination of an optimal tree path with the use of the simplex method was solved. For economic estimation, the capitalized-value method, which considers all costs of investment and operation, was used.

Ruan et al. (2009) and Ríos-Mercado et al. (2006) show that the mainline system is a vital part of natural gas network systems. The investment required for the mainline system is enormous, usually accounting for 80% of the total investment for this system. In general, the investment required for a gas pipeline depends on its operating parameters. Therefore, based on the characteristics of gas networks, optimization for investment becomes indispensable to gas-network design. A comprehensive and optimal mathematic model of a gas-network system is established in this study.

Bhaduri and Talachi (1988) presented a case study of optimization of the Qinghai gas pipeline in China to determine the optimum pipe size, compression facilities, pipeline route, operating pressure, and storage facilities, if required.

Andre et al. (2009) show a technique for solving the problem of minimizing investment costs on existing gas-transportation networks. The goal of this program is to find, first, the optimal location of pipeline segments to be reinforced and, second, the optimal sizes (among a discrete commercial list of diameters) under the constraint of satisfaction of demands with high-enough pressure for all users.

Installation and Operating Cost of Natural Gas Pipelines
Installation Cost of Natural Gas Pipelines. Actual cost data were obtained from a petroleum pipeline company for natural gas steel pipelines. These data have been processed and a formula has been obtained (Eq.1) for estimating the installation cost of gas pipelines in Egypt The mean deviation is 12.6%, which is a quite acceptable figure for this kind of project.

$$C1 = EL \times I \times (0.4023 \times D + 1E\text{–}14)\ 10^6. \qquad (1)$$

Cost of Compressor Stations. Bhaduri and Talachi (1988) state that the cost of compressor stations is a function of the pipeline length, initial compressor cost, and horsepower and is calculated as follows:

$$C2 = (EL / L) \times I \times C3. \qquad (2)$$

Mallinson et al. (1986) and Bykov et al. (2006) show that the horsepower (HP) of the compressor station is calculated from the following equation:

$$HP = \frac{10^6 \times T \times Z \times Q \times P_a \times k \times 144}{24 \times 3600 \times 550 \times T_{\text{std}} \times (k-1) \times \eta} \left[\left(P_d / P_s \right)^{(K-1)/K} - 1 \right]. \qquad (3)$$

Fuel Cost of Compressor Stations. The fuel cost of the compressor, $C6$, is obtained from the price of fuel, fuel consumption, horsepower, and the design distance:

$$C6 = (EL/L) \times F1 \times F2 \times \text{HP, L.E.} \qquad (4)$$

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TABLE 1—OPTIMAL DESIGN VARIABLES AT Q = 100 MMscf/D

Diameter (D, in.)	Suction Pressure (P_s, psia)	Discharge Pressure (P_d, psia)	Comp. Ratio (P_d/P_s)	Length (L, mile)	Total Cost or Objective Function (MM L.E./mile)
14	920.44	1,100	1.195	65	34.54183
16	1,011.41	1,100	1.087	65	19.91631
18	1,051.53	1,100	1.046	65	14.44829
20	1,071.53	1,100	1.026	65	12.23597
22	1,082.34	1,100	1.016	65	11.43733
24	1,088.56	1,100	1.011	65	11.32838
26	1,091.36	1,100	1.008	73.06	11.58387
28	1,093.46	1,100	1.005	80	12.04320

Cost of Maintenance and Utilities. The annual cost of maintenance and utilities of the compressor, $C7$, is determined from horsepower, design distance length of pipeline, and maintenance and utility charges:

$$C7 = 12 \times (EL/L) \times F3 \times HP, \text{ L.E/year.} \quad (5)$$

Cost of Labor and Supervision. The annual cost of labor and supervisions, $C8$, is estimated from the following equation:

$$C8 = 12 \times (EL/L) \times F4 \times HP, \text{ L.E/year.} \quad (6)$$

Objective Function

The objective function of the design and operation of a gas pipeline is the total annual cost of the pipeline, C, including the cost of installation of the pipeline, compressor stations, fuel consumption in compressor stations, maintenance and utilities, and cost of labor and supervision. The objective function is given by adding Eqs. 1, 2, and 4 through 6 as follows:

$$C\,(D, Q, L, P_d, P_s) = 0.4023 \times 10^6 \times D \times I \times EL$$

$$+ (EL/L) \times I \times C4$$

$$+ (EL/L)(I \times C5 + F1 \times F2 + 12 \times F3 + 12 \times F4)$$

$$\times \left[\frac{10^6 \times T \times Z \times Q \times P_a \times k \times 144}{24 \times 3600 \times 550 \times T_{\text{std}} \times (k-1) \times \eta} \left[(P_d / P_s)^{(K-1)/K} - 1 \right] \right]. \quad (7)$$

Assumptions. The following assumptions are used for long transmission gas pipelines in this study:

I. “Steady-state flow conditions” means that no any variables will be change with time.

II. Change of kinetic energy is small and can be neglected because the main loss is caused by friction, and when the kinetic energy is compared with friction energy, it is found to be very small.

III. Flow is isothermal. After each compressor station, the gas will gain some heat. This heat will dissipate into the ground after a few miles, while the transmission pipeline can reach to around 100 miles; then we consider that the temperature of gas is constant along the pipeline.

IV. Natural gas behaves as a real gas. This means that the compressibility effect is taken into account.

These assumptions will affect the calculation results and then the final conclusions.

Constraints

The objective function is used to optimize the design variables to minimize the total construction cost of natural gas transmission pipelines, including compressor stations, according to the following constraints.

Modified Panhandle Equation. Burnham and Corfield (1977) and Schroeder and Noble Denton (2001) show the equation that is most widely used in the design of long transmission lines and that is better for large diameters; it considers the compressibility factor.

$$Q = 737 \left(\frac{T_b}{P_b} \right)^{1.02} \left(\frac{P_d^{\,2} - P_s^{\,2}}{G^{0.961} TLZ} \right)^{0.51} D^{2.53}. \quad (8)$$

TABLE 2—OPTIMAL DESIGN VARIABLES AT Q = 200 MMscf/D

Diameter (D, in.)	Suction Pressure (P_s, psia)	Discharge Pressure (P_d, psia)	Comp. Ratio (P_d/P_s)	Length (L, mile)	Total Cost or Objective Function (MM L.E./mile)
18	896.698	1,100	1.227	65	73.72840
20	984.53	1,100	1.117	65	43.74486
22	1,029.55	1,100	1.0684	65	30.04975
24	1,054.78	1,100	1.0428	65	23.06594
26	1,069.81	1,100	1.0282	65	19.33971
28	1,079.19	1,100	1.0193	65	17.35695
30	1,085.26	1,100	1.0136	65	16.37211
32	1,089.32	1,100	1.0098	65	15.98793
34	1,029.47	1,039.77	1.01	80	16.25882
36	893.39	902.33	1.01	80	17.06342

TABLE 3—OPTIMAL DESIGN VARIABLES AT Q = 300 MMscf/D					
Diameter (D, in.)	Suction Pressure (P_s, psia)	Discharge Pressure (P_d, psia)	Comp. Ratio (P_d/P_s)	Length (L, mile)	Total Cost or Objective Function (MM L.E./mile)
18	557.73	1,100	1.972	65	357.6014
20	822.79	1,100	1.337	65	151.1655
22	936.91	1,100	1.174	65	86.77237
24	.997.12	1,100	1.103	65	56.99486
28	1,053.36	1,100	1.044	65	32.02457
32	1,076.2	1,100	1.022	65	23.33247
34	1,082.43	1,100	1.016	65	21.37408
36	1,086.8	1,100	1.012	65	20.25554
38	1,089.92	1,100	1.009	70.2	19.69065
40	1,023.73	1,033.97	1.01	80	19.80061
42	907.04	916.11	1.01	80	20.76304

Upper And Lower Constraints. The upper and lower constraints for the suction and discharge pressures of compressor stations, the diameter of pipeline, the length between each two compressor stations, and the compression ratio of compressor stations P_d/P_s were supplied by the Petroleum Pipeline Co. in Cairo to address the operating conditions in Egypt. These values are as follows:

$$\begin{aligned} &250 \text{ psia} \leq P_s \leq 1{,}100 \text{ psia} \\ &280 \text{ psia} \leq P_d \leq 1{,}100 \text{ psia} \\ &10 \text{ in.} \leq D \leq 48 \text{ in.} \qquad (9) \\ &50 \text{ miles} \leq L \leq 85 \text{ miles} \\ &P_d/P_s \leq 1.5 \end{aligned}$$

These are the upper and lower operating conditions in Egypt, but if we need to obtain optimal design variables at higher pressures than 1,100 psia ≈76 bar, we must change the value of discharge pressure P_d in Eq. 9 to the new value.

The objective function or the total cost is a function of diameter D, gas flow rate Q, length between each two consecutive compressor stations L, compression ratio of compressor stations P_d/P_s, and the total length of the gas pipeline EL. The software computer program LINGO is used to optimize the objective function C in Eq. 7 with the constraints in Eqs. 8 and 9.

Results and Discussion

The effect of diameter on the objective function or total cost per 1 mile per year is shown in **Tables 1 through 5.** For all the investigated flow rates, it was found that as diameter increases, the cost of pipeline increases, but the cost of the compressor station decreases. Hence, the total cost passes through a minimum value, after which it starts increasing again. The minimum value is established at D=24 in. when Q=100 MMscf/D (see Table 1). At this diameter, the total cost of pipeline including compressor station is 11.328 MM. L.E./year.mile. The optimal design variables are suction and discharge pressures, the compression ratio, and the length between each two successive compressor stations, which are 1,100 and 1,088.5 psia, and 1.011 and 65 miles, respectively.

From Table 2, at Q=200 MMscf/D the total minimum cost has been achieved at D=32 in. At this diameter, the total cost is 15.988 MM. L.E./year.mile. The optimal design variables are suction and discharge pressures, the compression ratio, and the length between each two successive compressor stations, which are 1,100 and 1,089.3 psia, and 1.0098 and 65 miles, respectively.

At Q=300 MMscf/D, the minimum value at which the total cost passes through a minimum is 19.69 MM. L.E./year.mile (Table 3). This minimum value is established at D=38 in. The optimal design variables are suction and discharge pressures, the compression ratio, and the length between each two successive compressor stations, which are 1,089.92 and 1,100 psia, and 1.009 and 70.2 miles, respectively.

TABLE 4—OPTIMAL DESIGN VARIABLES AT Q = 400 MMscf/D					
Diameter (D, in.)	Suction Pressure (P_s, psia)	Discharge Pressure (P_d, psia)	Comp. Ratio (P_d/P_s)	Length (L, mile)	Total Cost or Objective Function (MM L.E./mile)
20	522.54	1,100	2.105	65	523.9619
24	911.46	1,100	1.207	65	131.7632
28	1,016.6	1,100	1.082	65	61.83574
32	1,057	1,100	1.0398	65	37.84277
36	1,076	1,100	1.021	65	28.13875
40	1,086.23	1,100	1.013	65	24.11472
42	1,089.35	1,100	1.009	65	23.17795
44	1,091.44	1,100	1.0078	65	22.67903
46	1,093.14	1,100	1.006	65	22.49385
48	1,094.45	1,100	1.005	65	22.53722
50	1,095.4	1,100	1.004	65	22.74958

TABLE 5—OPTIMAL DESIGN VARIABLES AT Q = 500 MMscf/D

Diameter (D, in.)	Suction Pressure (P_s, psia)	Discharge Pressure (P_d, psia)	Comp. Ratio (P_d/P_s)	Length (L, mile)	Total Cost or Objective Function (MM L.E./mile)
22	552.74	1,100	1.99	65	601.1166
28	967.77	1,100	1.136	65	114.5153
32	1,033.93	1,100	1.06	65	62.42366
36	1,063.67	1,100	1.034	65	42.63378
40	1,078.61	1,100	1.019	65	31.73629
46	1,089.35	1,100	1.0097	65	26.24649
48	1,091.39	1,100	1.0078	65	25.56694
50	1,092.97	1,100	1.0064	65	25.21839
52	1,094.22	1,100	1.0052	65	25.11731
54	1,095.21	1,100	1.0043	65	25.20360
58	1,096.12	1,100	1.0035	75	25.77386

At Q=400 MMscf/D, the minimum total cost is established at D=46 in. (see Table 4). At this diameter, the construction cost of pipeline including compressor station is 22.679 MM. L.E./year.mile. The optimal design variables are suction and discharge pressures, the compression ratio, and the length between each two successive compressor stations, which are 1,093.14 and 1,100 psia, and 1.006 and 65 miles, respectively.

At Q=500 MMscf/D, the total minimum cost has been achieved at D=52 in. (see Table 5). At this diameter, the total cost is 25.117 MM. L.E./year.mile. The optimal design variables are suction and discharge pressures, the compression ratio, and the length between each two successive compressor stations, which are 1,094.22 and 1,100 psia, and 1.005 and 65 miles, respectively.

In Tables 3 through 5, it is worth mentioning that in the cases of D=18 in. at Q=100 MMscf/D, D=20 at Q=400, and D=22 at Q=500, there are unaccepted solutions, because violations in constraints have occurred where the obtained compression ratios were 1.972, 2.105, and 1.99, respectively. These values are greater than the maximum specified value (1.5).

Tables 1 through 5 also indicate that when the pipeline diameter significantly increases, the suction pressure increases. As a result, the compression ratio becomes close to unity. This means that the pipeline can be used to transport the whole quantity of gas flow rate without the need for using compression stations. However, it is obvious that the total cost is extremely high.

From these optimization results, we can find the optimal design variables and operation of transmission pipelines over flat terrain pertaining to the operating conditions in Egypt. At the same time, we can apply the same methodology to find the optimal design variables and operation of transmission pipelines over flat terrain according to a different objective function and other constraints for any research applications in any country.

Conclusions

The objective function is given by a nonlinear function of flow rates and pressures. The optimization problem has been solved with a number of decision variables and the number of constraints to find the optimal design variables and operation of transmission pipelines over flat terrain. The design variables for transmission pipelines carrying 100 to 500 MMscf/D of natural gas with different diameters and compressor compression ratio between 1 and 1.5 have been optimized.

The objective function includes the installation cost of pipelines, compressor stations, fuel consumption in compressor stations, maintenance, labor, and supervision. The software computer program LINGO is used to obtain the solution procedure for optimal design and operation of transmission gas pipelines. For all the investigated flow rates, the optimum design variables are show in **Table 6.**

Nomenclaure

$C1$ = gas pipeline construction cost (Egyptian pound L.E./year)
$C2$ = total cost of compressor station, L.E./year
$C3$ = initial cost of compressor station and is equal to ($C4$+$C5$×HP), L.E.
$C4$ = fixed cost of compressor station, L.E.
$C5$ = cost of one installed HP, L.E.
D = pipe diameter, in.
EL = total length of pipeline, miles
(EL/L) = term represents the number of compressor stations
$F1$ = internal charge for fuel, scf
$F2$ = fuel consumption, BTU/bhp-hr
$F3$ = maintenance and utility charges per month
$F4$ = salaries of labors and supervisions per month for compressor station

TABLE 6—OPTIMUM DESIGN VARIABLES FOR ALL INVESTIGATED FLOW RATES

Diameter (D, in.)	Suction Pressure (P_s, psia)	Discharge Pressure (P_d, psia)	Comp. Ratio (P_d/P_s)	Length (L, mile)	Total Cost or Objective Function (MM L.E./mile)
24	1,088.56	1,100	1.011	65	11.32838
32	1,089.32	1,100	1.0098	65	15.98793
38	1,089.92	1,100	1.009	70.2	19.69065
46	1,093.14	1,100	1.006	65	22.49385
52	1,094.22	1,100	1.0052	65	25.11731

G = gas specific gravity, M.W/29
I = interest rate on capital investment per year
k = isentropic index of the natural gas
L = the length between two consecutive compressor stations, miles
MW = molecular weight of the natural gas
P_a = atmospheric pressure, psia
P_b = pressure base, psia
P_d = discharge pressure of compressor, psia
P_s = suction pressure of compressor, psia
Q = flow rate, MMscf/D
T = prevailing inflowing temperature, degrees
T_b = temperature base, °R
T_{std} = temperature of the gas at standard conditions, °R
Z = compressibility of the gas at average pressure and temperature, dimensionless
η = compressor efficiency

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