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Cost Minimization Model of Gas Transmission Line for Indonesian SIJ Pipeline Network

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Abstract. Optimization of Indonesian SIJ gas pipeline network is being discussed here. Optimum pipe diameters together with the corresponding pressure distribution are obtained from minimization of total cost function consisting of investment and operating costs and subjects to some physical (Panhandle A and Panhandle B equations) constraints. Iteration technique based on Generalized Steepest-Descent and fourth order Runge-Kutta method are used here. The resulting diameters from this continuous optimization are then rounded to the closest available discrete sizes. We have also calculated toll fee along each segment and safety factor of the network by determining the pipe wall thickness, using ANSI B31.8 standard. Sensitivity analysis of toll fee for variation of flow rates is shown here. The result will gives the diameter and compressor size and compressor location that feasible to use for the SIJ pipeline project. The Result also indicates that the east route cost relatively less expensive than the west cost.

1 Introduction

With large natural gas resources and the increase demand of domestic gas consumption in Indonesia, the need to extend the existing pipeline network and to build new pipelines connecting several resources and consumers has been growing significantly in the last decade. In order to connect the gas fields to the costumers which are normally several hundred kilometers away, it is very important to build an integrated and efficient transmission pipeline. The role of optimization techniques is very crucial to minimize the investment and operating cost.

The transmission network being considered here is approximately 1200 km long connecting two islands in Indonesia. This Pipeline is estimated to deliver about 800 MMSCFD gas from 2 sources with two possible choices of routes, which are west route and east route. This network is described in section 2. The parameters being optimized here are pipe diameters, pressure at each node and compressor horse power.

Several commercial softwares being used in gas industries are not directly built on the basis of cost optimization. Here we use mathematical model for the pipeline cost as a function of pipe diameters and pressures, which satisfy some physical constraints. Relevant technical, economical and physical aspects related to investment and operating costs are taken into account. There are several literatures on pipe line optimization (see for example in [1, 2, 3]), most of them use simplified model either in the construction of cost function or in the constraints. Recently a complete cost model which is suitable for Indonesian gas fields was proposed in [4]. This model turns to be useful both for transporter companies and gas field owners. Applications of the model in different fields and different conditions could be seen in [5, 6]. This cost model is presented in section 4. This cost function will be the objective function for our optimization. In section 3, we review Panhandle A and Panhandle B equations describing the flow equation in each segment of pipes. This flow equation together with maximum pressure in each segment and maximum discharge pressure of compressors will function as constraints for the minimization techniques which are described in section 6. Wall thickness calculation which is related to the strength of the pipe is discussed in section 5.

The optimum diameters that are obtained from the optimization process will be adjusted to the nearest sizes which are available in the market. The safety factor of the pipeline will be calculated by determining the pipe wall thickness using ANSI B.31 standard. These results are also adjusted to the real sizes available in the market.

2 Description of SIJ Network

SIJ pipeline transmission network is to be chosen between two possible (west and east) routes, both connecting the inlet point A with the outlet point SN as shown in figure 1. The total length of each route is about 1200 km. Only the segment OF-SN lie off-shore and the rest of the network lies on-shore. In order to anticipate large pressure drop, compressor are planned to be located in four positions.

Elevation in each segment due to bottom topography is shown in figures 2 and 3. These elevations could contribute significantly to the pressure drops along the transmission line and will be taken into account in the computation in the later sections. The objective here is to find optimum pipe diameters for each route taking into account some necessary constraints.

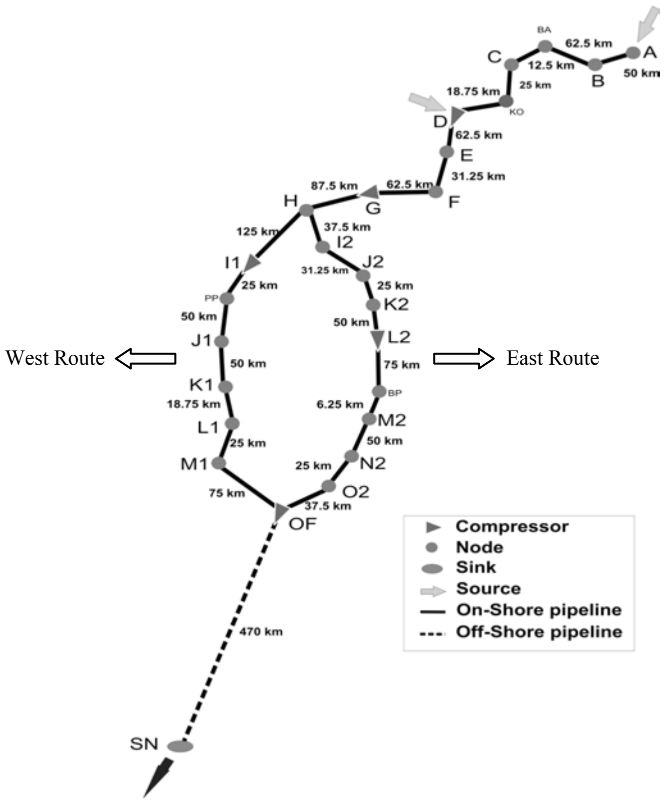

Figure 1 Map of the network.

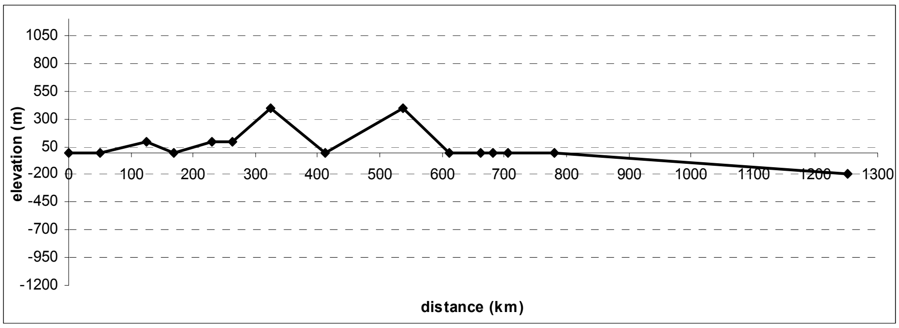

Figure 2 Elevation map (west route).

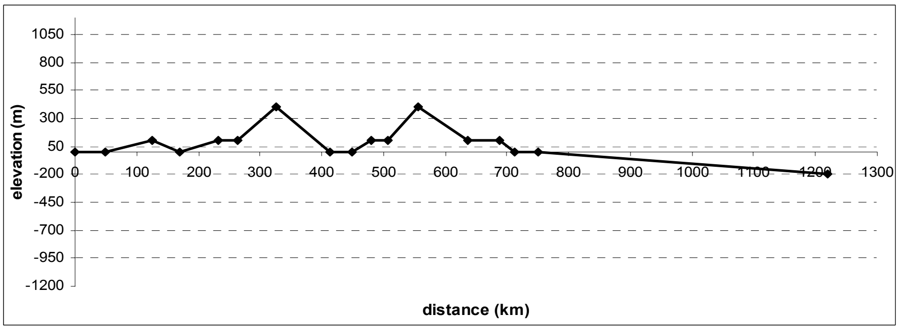

Figure 3 Elevation map (east route).

3 Pipe Flow Equation

Flow equation in a single segment of transmission pipeline is generally derived from the steady state condition of the energy balance equation, taking into account the empirical friction factor .The equation is written in term of pressure gradient as follows [7]

$$\frac{dp}{dl} = \frac{g}{g_c}\rho \sin\theta + \frac{f\rho v^2}{2g_c d} + \frac{\rho v dv}{g_c dl} \ , \tag{1}$$

where

f = friction factor

θ = angle of elevation

Through out this paper we consider the case of steady state flow; therefore equation (1) is reduced to steady state flow equation

$$\frac{dp}{dl} = \frac{g}{g_c}\rho \sin\theta + \frac{f\rho v^2}{2g_c d} . \tag{2}$$

Here we assume that the adiabatic condition prevails and temperature through out the pipe is constant. Friction between gas and inside wall of the pipe will cause a loss of mechanical energy during the flow. This energy loss depends on the viscosity of the gas and the roughness of inside wall. The friction factor depends also on the flow rate of the gas and the pipe diameter. Two models of friction factor are used here, which are Panhandle A and Panhandle B, as shown in equation (3) and (4),

$$f = \frac{0.085}{N_{\mathrm{Re}}^{0.147}} \tag{3}$$

$$f = \frac{0.015}{N_{\mathrm{Re}}^{0.0392}} \tag{4}$$

respectively. Note that the flow equation (2) will function as a constraint relating pressure and diameter in each segment of pipe.

4 Cost Model Structure

In this section the construction of the total cost model adopted from [4] will be discussed. This total cost will be used as the objective function for the optimization process. The cost is separated into two parts, the (total) pipe cost and the (total) compressor cost as follows

$$\text{TOTAL COST} = \left[\text{INVESTMENT COST} + \text{OPERATION COST}\right]_{\text{PIPE}} + \left[\text{INVESTMENT COST} + \text{OPERATION COST}\right]_{\text{COMPRESSOR}}$$

with some assumptions ,

a) gas in the pipeline is single-phase flow
b) gas flow in the pipeline is steady state
c) gas temperature along each segment of pipe is constant
d) gas temperature does not change after coming out of compressor
e) gas deviation factor (Z) along each segment of pipe is constant and does not change after coming out of compressor
f) compressor type is centrifugal
g) tax, insurance, and other economic calculations are excluded.

Investment Cost

Here a uniform capital recovery is used for annual investment cost. The formula is given as follows

$$A = P\frac{(1+r)^n r}{(1+r)^n - 1} \tag{5}$$

where

A = uniform annual capital cost
P = present value of total investment cost
r = annual interest rate
n = life time of the equipment.

Investment Cost for Pipeline

The total investment cost for a segment of pipe is given as follows

$$Cpipe = (1 + Rp)CpL^{l}d^{m} \quad (6)$$

where

$Cpipe$ = pipe investment cost (US$)

Rp = ratio between pipe installation cost and the pipe price itself

Cp = unit price of pipe (US$/ft.inch), obtained from available data

L = length of pipe (feet)

d = diameter of pipe (inch)

l,m = non-linearity constants obtained from regression.

The total investment cost for piping consists of pipe material, and installation cost. The annual cost based on capital recovery approach as indicated in equation (5) is

$$CIP = \frac{r(1+r)^{n}(1+Rp)CpL^{l}d^{m}}{(1+r)^{n}-1} \quad (7)$$

where

CIP = annual investment cost of pipe (US$/year)

r = annual interest rate.

Compressor Investment Cost

Investment cost of compressor is given by the following model

$$Ccomp = Chp\ ghp^{b}$$

where

Chp = compressor price (US$/hp)

ghp = compressor power (hp)

b = non-linearity constant obtained from regression.

The compressor is centrifugal type. Based on the above assumptions, the power of compressor can be written as

$$ghp = \frac{6250}{2061} \frac{Q\ Pb\ T\ Z\left(\left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{k\ Ep}\right)} - 1\right)k}{Tb\ (k-1)} + bl + sl \tag{8}$$

where

Q	= inlet gas flow-rate for the compressor (MMscfd)
Pb	= base pressure (psia)
Tb	= base temperature (^{o}R)
T	= gas temperature (^{o}R)
Z	= gas deviation factor
P_1	= inlet pressure (psia)
P_2	= outlet pressure (psia)
k	= adiabatic exponent
Ep	= efficiency of compressor (%)
bl, sl	= bearing losses and seal losses.

The total investment cost for compressor is obtained as follows

$$Ccomp = Chp\left(\frac{6250}{2061} \frac{Q\ Pb\ T\ Z\left(\left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{k\ Ep}\right)} - 1\right)k}{Tb\ (k-1)} + bl + sl\right)^{b} \tag{9}$$

We obtain the annual investment cost of compressor, CIC in US$/year as follows

$$CIC = \frac{r\,(1+r)^n}{(1+r)^n - 1} Chp \left(\frac{6250}{2061} \frac{Q\;Pb\;T\;Z \left(\left(\frac{P_2}{P_1} \right)^{\left(\frac{k-1}{k\;Ep} \right)} - 1 \right) k}{Tb\;(k-1)} + bl + sl \right)^b \tag{10}$$

Pipeline Operating Cost

The annual operating cost of pipeline is assumed to be proportional to the pipe investment cost as follows

$$OCpipe = \frac{r\,(1+r)^n (1+Rp)\;Cfp\;Cp\;L^l\;d^m}{(1+r)^n - 1} \tag{11}$$

where

Ocpipe = pipe operating cost (US$/year)

Cfp = fraction, a ratio of pipe operation cost to investment cost.

Compressor Operating Cost

Factors affecting the compressor operating cost are electricity cost for compressor operation (if electricity is used), maintenance cost, and other costs involved in compressor system.

The operating cost is proportional to the electricity cost, as follows

$$OCcomp = x\;Lstr$$

with $x > 1$ and *Lstr* represents the electricity cost. For convenience, *x* is written as

$$x = 1 + Copcomp$$

with *Copcomp* represents a fraction of compressor operating cost excluding its electricity cost. The compressor operating cost can be written as

$$OCcomp = (1 + Copcomp)\;Lstr.$$

To obtain the electricity cost, the unit used in equation (8) is converted from *horsepower* to *Kwh*. So we have

$$Lstr = \frac{1}{8760}\left(19809.32047 \frac{Q\,Pb\,T\,Z\left(\left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{kEp}\right)} - 1\right)k}{Tb(k-1)} + 6532.321518\,(bl + sl)\right) CeHy \qquad (12)$$

where

Ce : electricity cost (US$/Kwh)

Hy : operating compressor hours in a year.

Toll Fee

Toll fee is a service fee for delivering a unit of gas through a segment of pipeline. Toll fee can be charged per unit length (US$/MSCF/km) or for a certain distance ($/MSCF). Due to the effect of "economic of scale", toll fee is usually charged on distance basis. An illustration for calculating the toll fee is presented as follows.

a) Consider N segment transmission pipeline, then we have

$$CIP = CIP_1 + CIP_2 + \ldots + CIP_N \qquad (13)$$

$$OCpipe = OCpipe_1 + OCpipe_2 + \ldots + Ocpipe_N\,. \qquad (14)$$

b) Gas that flows along the pipeline which is located after compressor is influenced by the compressor power, no matter how small it is. Due to this fact, we will add the *CIC* and *OCcomp* costs to each segment of pipe that is influenced by the compressor based on the length of the pipe. Thus, we have

$$CIC_i = \frac{L_i}{Lf} CIC\,, \qquad (15)$$

$$OCcomp_i = \frac{L_i}{Lf} OCcomp \qquad (16)$$

with L_i as the length of a segment of pipe which is located after compressor, and *Lf* as the total length of all pipes which are located after compressor.

c) Toll fee for each segment of pipe is

$$TF_i = \frac{CIP_i + OCpipe_i + CIC_i + OCcomp_i}{Q_i \times 365 \times 1000} \tag{17}$$

with

TF_i = toll fee on segment of –*I* (US$/MSCF).

Note that in practice the location of compressors represented by the parameters L_i could be taken as optimizing parameters.

5 Wall Thickness Calculation for Transmission Pipe

Wall thickness calculation of the pipeline is obtained by using ANSI B 31.8 standard [10]. This standard is considering some factors, such as pipe design, diameter, pressure and the type of the pipe. The Equation of the wall thickness is given as

$$t = \frac{P.d_0}{2.(F.E.T.S)} \tag{18}$$

with :

t = wall thickness (inch)

P = pressure (psia)

d_0= outside diameter (inch)

S = minimum pipe strength (psi)

F = design factor

E = join factor

T = temperature derating factor.

Design factor depends on the location of the pipe. Some type of design factor can be seen below.

Class	Design Type	Design Factor
1	Oil and gas field or *unpopulated area*	0.72
2	Semi-developed area, minimum facility	0.6
3	Compressor station area.	0.5
4	Commercials area .	0.4

Join factor is the parameter that depends on pipe material. The value of the join factor is

1.00 for seamless, ERW pipe,

0.80 for furnace lap and electrical fusion welded pipe,

0.60 for furnace butt welded pipe.

Temperature derating factor is a measurement of temperature's effect to the pipe material. This value gives the relation between the temperature and its impact to the pipe material. The value of this coefficient is given in the table below.

Temperature (^{o}F)	Derating Factor
-20^{o} – 250^{o}	1.000
300^{o}	0.967
350^{o}	0.933
400^{o}	0.900
450^{o}	0.867

6 Optimization Method

Here we minimize an objective (Total Cost) function, which is nonlinear subject to a set of constraints consisting nonlinear equations and inequalities. We denote the objective function by *C(X)* and the constraints $K_j(X)=0, j=1..J_1, K_j(X)\le 0, j=J_1..J_2$, where the components of X are pipe diameters, gas pressures and compressor horse power, the equality constraints are the flow equations in each segment of pipes, and the inequality constraints are the maximum pressure conditions of pipes which represent the strength of the pipes. Note that the linear technique approach (see for example in [1, 2]) is no longer workable in this model since high non-linearity terms involve in objective function as well as in constraints. Other approach using heuristic techniques were also done (see in [8, 9]). The continuous approach being used here is chosen to accommodate more complicated physical condition such as surface elevation and if necessary the change of temperature can also be included.

From a given initial condition X_0, we select the direction, which gives the largest decrease of the cost. This direction is based on the *Generalized Steepest-Descent* which is given by the gradient of each constraint ($\sum_{j=1}^{J_1}\alpha_j \nabla K_j(X_n)$). The procedure for constrained minimization is given as follows

$$\frac{dX}{dt} = -\nabla C(X) + \sum_{j=1}^{J_1}\alpha_j \nabla K_j(X)] , \tag{19}$$

where t is iteration parameter and α_j has to satisfy the system of linear equations

$$\sum_{j=1}^{J_1} \alpha_j \nabla K_j(X) \circ \nabla K_i(X) = \nabla C(X) \circ \nabla K_i(X), i = 1..J_1. \qquad (20)$$

The *Fourth Order Runge Kutta* method is then applied to the dynamical equation (19) to produce the optimum result. Below is the algorithm for the computational process.

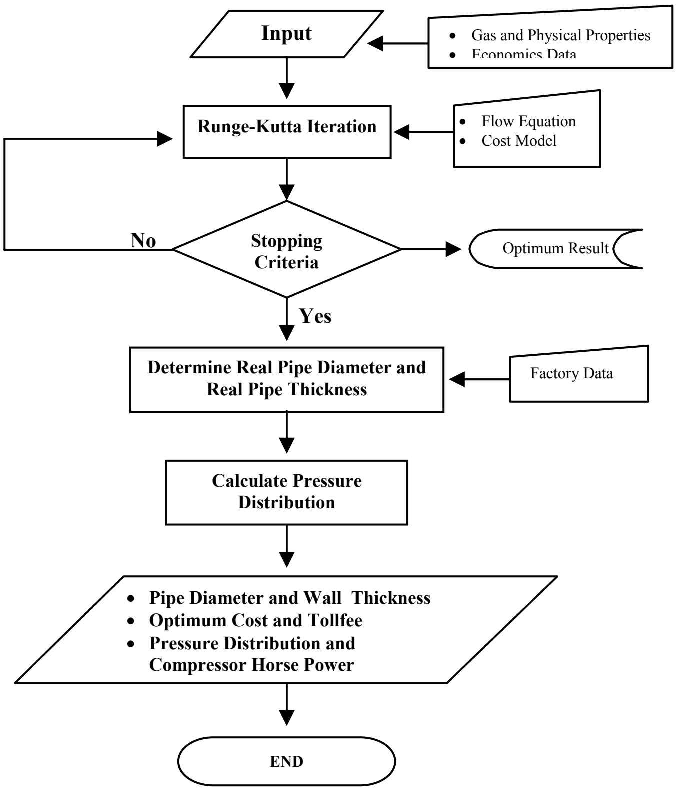

Figure 4 Numerical computation flow chart.

7 Numerical Results and Analysis

Here we present numerical result for the SIJ pipeline transmission network. The set of data that is used in the computation is given in table 1.

Symbol	Parameter	Value
C_e	Electricity cost	0.03 US$/kWh
H_y	Time operation	8760 hours
C_p	Cost for a pipe / diameter / length	0.569 US$/in/ft
L_{fp}	Pressure fraction loss caused by valve, bend, fitting, etc.	0.35
E_p	Compressor efficiency	0.9
R_p	Comparison between installation cost and pipe cost	Onshore : 1.4 Offshore: 3
C_{fp}	Yearly maintenance cost	0.2
Sl	Sealing losses	20 hp
Bl	Bearing losses	30 hp
R	Annual interest rate	12 %
C_{HP}	Compressor cost / horse power	2000 US$/hp
F	Design factor	0.6
E	Join factor	0.8
T	Temperature derating factor	1
S	Minimum pipe strength	65000 psi
	Pipe price	800 US$/ton
SGg	Gas Specific Gravity	0.617
Z	Z factor	0.8
T	Temperature	125 ^{o} F

Table 1 Data for Computation.

No	Segments	Length (km)	Flowrate (MMSCF/D)	Elevation (meter)
1	A-B	50	341	0
2	B-C	75	341	100
3	C-D	43.75	341	0
4	D-E	62.5	841	100
5	E-F	31.25	841	100
6	F-G	62.5	841	400
7	G-H	87.5	841	0
8	H-I1	125	841	400
9	I1-J1	75	841	0
10	J1-K1	50	841	0
11	K1-L1	18.75	841	0
12	L1-M1	25	841	0
13	M1-OF	75	841	0
14	OF-SN	470	841	(200)

Table 2 Summary of physical parameters, west scenario.

No	Segments	Length (km)	Flowrate (MMSCF/D)	Elevation (meter)
1	A-B	50	341	0
2	B-C	75	341	100
3	C-D	43.75	341	0
4	D-E	62.5	841	100
5	E-F	31.25	841	100
6	F-G	62.5	841	400
7	G-H	87.5	841	0
8	H-I2	37.5	841	0
9	I2-J2	31.25	841	100
10	J2-K2	25	841	100
11	K2-L2	50	841	400
12	L2-M2	81.25	841	100
13	M2-N2	50	841	100
14	N2-O2	25	841	0
15	O2-OF	37.5	841	0
16	OF-SN	470	841	(200)

Table 3 Summary of physical parameters, east scenario.

Pipe specification is X-65**.** Maximum discharge pressures are controlled not more than 1000 psia. Here we will compare the optimization result between Panhandle A and Panhandle B. The complete data of the pipeline network can be seen in table 2 and 3.

The results of numerical computation and analysis for East and West route will be presented in two forms, which are the optimum result and the practical result.

7.1 Optimum Result

The optimum result is directly obtained from numerical computation, as well as the number and the position of compressors. Here the compressors are placed in every node on the route and the process will eliminate unnecessary compressor in the certain position. At the end, we will obtain the optimum number of compressor in the certain position, beside the optimum diameter and horse power. The result of optimum condition can be seen in table 4 and 5 below.

Note that for both routes, the optimum results place several compressors in almost all nodes. This may not be practical in the field. Practical results which are preferable in reality are shown in the next section.

Data		Optimization Result				
Distance (mile)	**Flowrate** (MMSCFD)	**Outside Diameter** (inch)	**Real Pressure** (psia)	**Thickness** (inch)	**Horse Power** (HP)	**Toll fee** (US$MSCF)
31	341	26	704 - 632	0.344	0	0.03
46.5	341	24	935 - 800	0.406	5,641	0.06
27.125	341	28	950 - 926	0.5	2,456	0.04
38.75	841	36	926 - 841	0.625	0	0.02
19.375	841	36	841 - 800	0.562	0	0.01
38.75	841	34	971 - 849	0.625	6,711	0.03
54.25	841	34	968 - 852	0.625	4,511	0.04
77.5	841	36	948 - 760	0.625	3,693	0.06
46.5	841	36	956 - 896	0.625	7,969	0.04
31	841	36	896 - 832	0.625	0	0.02
11.625	841	36	832 - 807	0.562	0	0.01
15.5	841	36	807 - 773	0.562	0	0.01
46.5	841	34	959 - 846	0.344	7,468	0.04
291.4	841	38	957 - 350	0.688	4,259	0.34
		Annual Cost (US$/year)	205,570,700			
		Total Toll fee (US$/MSCF)	0.75			
		Present Value (US$)	1,535,499,000			

Table 4 Optimum result for *West Route*, using Panhandle A equation.

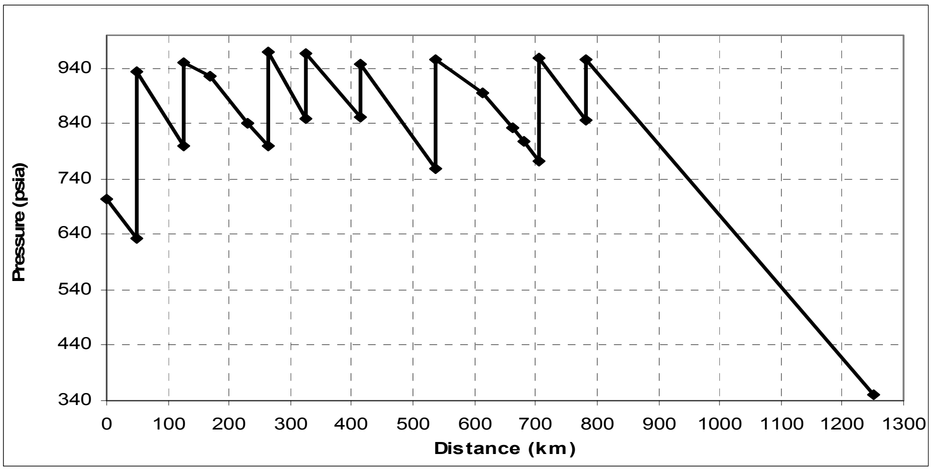

Figure 5 Pressure distribution for Optimum Result *West Route*.

Data		Optimization Result					
Distance (mile)	**Flowrate** (MMSCFD)	**Outside Diameter** (inch)	**Real Pressure** (psia)	**Thickness** (inch)	**Horse Power** (HP)	**Toll fee** (US$/MSCF)
31.00	341	26	701 - 629	0.344	0	0.03
46.50	341	24	931 - 795	0.406	5,642	0.06
27.13	341	28	944 - 920	0.5	2,456	0.04
38.75	841	36	920 - 835	0.625	0	0.02
19.38	841	36	835 - 793	0.562	0	0.01
38.75	841	34	962 - 840	0.625	6,711	0.03
54.25	841	36	957 - 880	0.625	4,511	0.04
23.25	841	36	880 - 832	0.562	0	0.02
19.38	841	36	832 - 783	0.562	0	0.01
15.50	841	34	972 - 934	0.625	7,512	0.02
31.00	841	34	934 - 830	0.562	0	0.02
50.38	841	36	967 - 892	0.625	5,281	0.04
31.00	841	34	892 - 806	0.562	0	0.02
15.50	841	34	961 - 931	0.625	6,100	0.02
23.25	841	34	931 - 870	0.562	0	0.01
291.40	841	38	957 - 350	0.688	3,291	0.34

Annual Cost (US$/year)	201,017,000
Total Tollfee (US$/MSCF)	0.74
Present Value (US$)	1,501,485,000

Table 5 Optimization result for *East Route*.

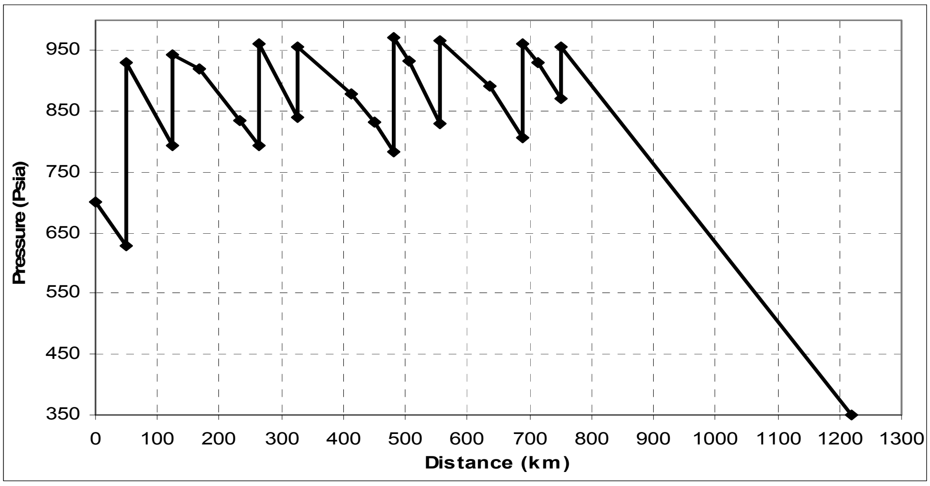

Figure 6 Pressure distribution for Optimum case *East Route*.

7.2 Practical Result

The optimum result may not be practical and applicable in the real condition, because the positions of the compressors are not feasible for practical condition. Here the compressor positions are relocated (if necessary) in selected position or node, with the distance in between 150-200 kilometers each. The result can be seen in table 6 and 7 below.

Data		Optimization Result				
Distance (mile)	**Flowrate** (MMSCFD)	**Outside Diameter** (inch)	**Real Pressure** (psia)	**Thickness** (inch)	**Horse Power** (HP)	**Toll fee** (US$ /MSCF)
31	341	30	736 - 703	0.406	0	0.04
46.5	341	30	703 - 643	0.375	0	0.06
27.125	341	30	643 - 615	0.344	0	0.03
38.75	841	36	974 - 891	0.625	16,309	0.05
19.375	841	36	891 - 852	0.562	0	0.01
38.75	841	36	852 - 747	0.562	0	0.02
54.25	841	36	988 - 916	0.625	9,741	0.05
77.5	841	36	916 - 725	0.625	0	0.05
46.5	841	36	985 - 928	0.625	10,706	0.05
31	841	36	928 - 866	0.625	0	0.02
11.625	841	36	866 - 842	0.562	0	0.01
15.5	841	36	842 - 809	0.562	0	0.01
46.5	841	36	809 - 708	0.344	0	0.03
291.4	841	38	957 - 350	0.688	10,536	0.35

Annual Cost (US$/year)	212,967,000
Total Toll fee (US$/MSCF)	0.77
Present Value (US$)	1,590,745,000

Table 6 Practical-Optimum result for *West Route*.

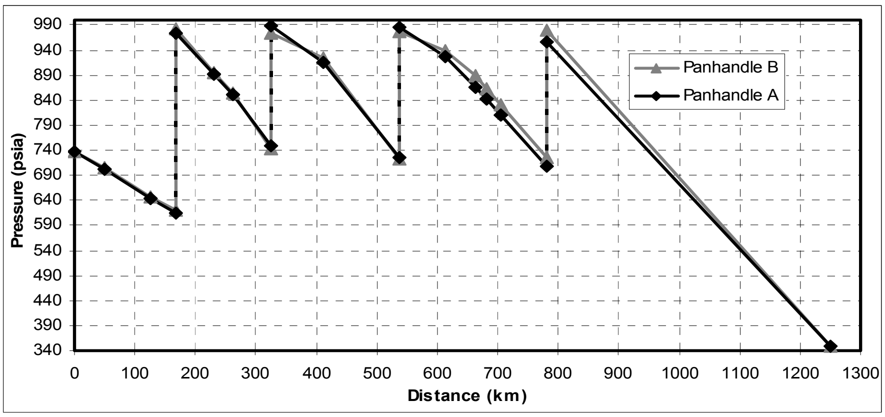

Figure 7 Pressure distribution for Practical-Optimum case *West Route*.

7.3 Analysis

From section 7.1, we obtain the optimum result of SIJ pipeline network. The compressor is located in every node and the numerical process eliminates unnecessary compressor to obtain the optimum number of compressor. For the west route, from 14 compressor placed, the process decrease it into 8 compressor (table 4) and for east route, the number decreases from 16 into 8 compressor (table 5). However, in this case, the numbers of compressor still not suitable for practical utilization, because the distance of each compressor is not long enough. The diameter size is also obtained with various numbers, which make it not practical for real condition, such as if there is any maintaining process, cleaning process, etc.

Data		**Optimization Result**				
Distance (mile)	**Flowrate** (MMSCFD)	**Outside Diameter** (inch)	**Real Pressure** (psia)	**Thickness** (inch)	**Horse Power** (HP)	**Toll fee** (US$/MSCF)
31.00	341	30	734 - 700	0.406	0	0.04
46.50	341	30	700 - 640	0.375	0	0.06
27.13	341	30	640 - 612	0.344	0	0.03
38.75	841	36	969 - 886	0.625	16,312	0.05
19.38	841	36	886 - 847	0.562	0	0.01
38.75	841	36	847 - 742	0.562	0	0.02
54.25	841	36	980 - 907	0.625	9,741	0.05
23.25	841	36	907 - 860	0.562	0	0.02
19.38	841	36	860 - 812	0.562	0	0.01
15.50	841	36	812 - 779	0.562	0	0.01
31.00	841	36	779 - 687	0.5	0	0.02
50.38	841	36	973 - 899	0.625	12,231	0.05
31.00	841	36	899 - 836	0.625	0	0.02
15.50	841	36	836 - 810	0.562	0	0.01
23.25	841	36	810 - 759	0.562	0	0.02
291.40	841	38	957 - 350	0.688	8,085	0.34
		Annual Cost (US$/year)	208,781,600			
		Total Toll fee (US$/MSCF)	0.75			
		Present Value (US$)	1,559,483,000			

Table 7 Optimization-practical result for *East Route*.

The second result, which is shown in section 7.2, is rather more practical. Here the compressor placement only in 4 positions (table 6, table 7), with each distance in between 150-250 km. Here, for both route, the diameter results are obtained more uniformly than previous case. For the onshore pipeline, the diameter is 30 and 36 inches. This is caused by the differences of the flowrate in those pipelines.

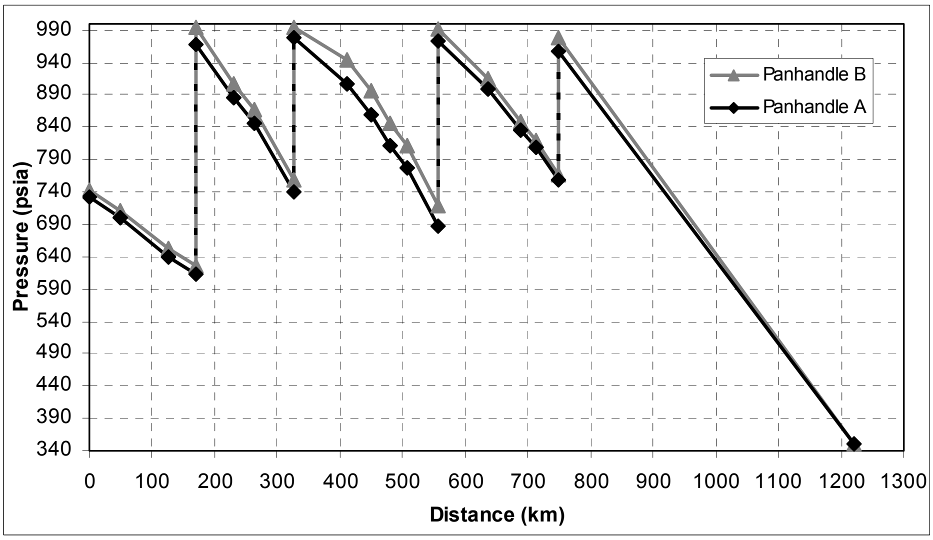

Figure 8 Pressure distribution for Practical-Optimum case *East Route*.

The offshore pipeline is about 470 km, and only uses 1 compressor with discharge pressure at 1000 psia. This condition happens because it is not preferable to put a compressor station in the middle of the ocean. Due this condition, the pipe diameter on the offshore area has to be larger than the onshore pipeline diameter, which is 38 inches.

8 Sensitivity Analysis

A sensitivity analysis is usually performed to observe the changes of variable of interest due to the changes of parameter. Here we make some sensitivity analysis for toll fee, with respect to flow rate. The result can be seen in figure 7.

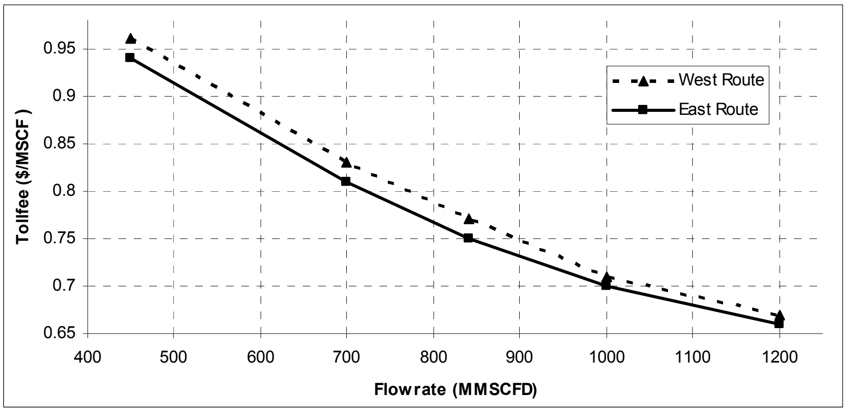

Figure 9 Toll fee sensitivity analysis.

The optimization result is also giving a different result of diameter. The larger flow rate implies the larger diameter, but gives smaller toll fee value.

9 Conclusion

We have presented the optimum SIJ transmission (east and west) networks resulting from minimization of total cost function subject to constraints in the forms of flow equation in each segment pipe, maximum strength of pipe and additional constraints related to compressor. The computations are performed with fourth order Runge Kutta method. The optimum diameters resulting from the continuous optimization are then being used to find the closest sizes available in the market. Results indicate that the east route is relatively less expensive than the west route.

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