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A Detailed Approach to Mechanical Design of Gas Pipeline Network System

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Abstract

The developed optimization models for flow throughput and pressure drop along with gas pipeline network in the thesis titled, "Flow Optimization in Natural Gas Pipeline" confirmed lack in an economy in the operation of the inline compressors. The developed optimization models employed Panhandle-A equation as base the base equation. The work is a case study of pipelines of some oil producing companies in Nigeria. Further observed, there were increased flow throughput and a reduction in the overall line pressure drop. The nominal line diameter was 36" (0.9144m). The lack in the economy due to the cost of the compressors and the power consumed at the optimal level of performance triggered this work. The research work confirmed that saving in cost and operation of the inline compressors could only be achievable if the operating upstream/downstream pressure is more than the range 81—63bar at nominal pipe diameter of 36" (0.9144m). At nominal pipe diameters of 43" (1.0922m) and 50" (1.27m) economy in the operation of gas pipeline assets and facilities was attainable at upstream/downstream pressures over 81—63bar. The nominal pipe thickness is limited to 0.05m to 0.10m. The new design concepts give flexibility in design, material selection, and installation of gas pipeline network system.

Keywords: Developed Optimization Models; Increased Flow Throughput; Lack in Economy; Pipeline Network System.

1. Introduction

A lot of gas equations, correlations and optimization models had been developed for operations, design, and installation of gas pipeline network system.

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Modern gas equations for pressure-capacity assessment of gas pipeline system are Weymouth equation, Panhandle-A, and modified Panhandle-B equation [1]. Gas pipeline mechanical design concept is an advanced area of study. The ANSI/ASME B31.8 standard is a stringent code for the design and installation of gas pipeline assets and facilities [2]. This standard code covers design and installation parameters for nominal pipe thickness, flow velocity considerations; compressors, valves, fittings, and flange design. This research work developed design and installation parameters for gas pipelines utilizing flow optimization models developed by the researchers coupled with the work on uplift resistance of a gas pipeline [3, 4, 5]. The developed flow optimization models are from previous research work [1]. It has been extended with operating and geometric data of five operating gas pipelines in Nigeria terrain. The approach to the mechanical design concept was to work over a range of nominal pipe thickness to generate the designed wall thickness over a range of given upstream and downstream pressures. All the prevailing stresses are it circumferential (hop) stress, longitudinal stress, radial stress, and shearing resistance were determined by the computational method. Other parameters such as pipe support spacing, the maximum deflection, maximum bending moment, the restoring force were also determined by computational approach. Optimal compressor power and operational compressor power were also determined. The developed design models are flexible enough to handle gas pipeline design problem out the range of functional and geometric data specified in this work.

2. Study Significance

The significance of this study concerns the generated design parameters. The parameters could aid in the selection of pipe materials knowing the prevailing stresses. Compressor sizing and spacing of pipe supports during installation is the beauty of this work.

3. Relevant Design Equations

The appropriate design equations are from previous works of the researcher [1, 3, 4]. The design equations formulated regarding stresses and load diagrams 1 to 5.

The hoop or circumferential stress expressed as :

$$\sigma_1 = \frac{Pd_1}{2t} \quad (1)$$

The longitudinal stress acting along the pipe wall parallel to the longitudinal axis given as :

$$\sigma_2 = \frac{Pd_1}{4t} \quad (2)$$

The expression for the radial stress goes thus;

$$\sigma_3 = \frac{Pd_1 - P_{ext}\left(d_1 + t\right)}{d_1 + t/2} \tag{3}$$

The resultant external load intensity on the structure expressed as:

$$P_{ext} = P_{atm} + P_{earth} + P_c + P_w + P_p \tag{4}$$

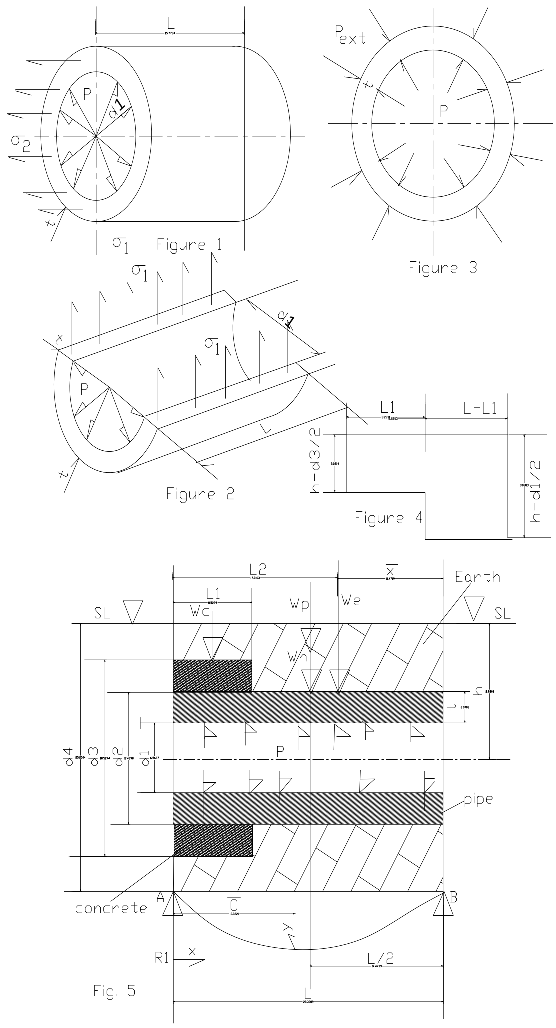

Figure 1: stresses and load geometry (diagrams 1 to 5)

The different load components are designated as :

(i) If the pipe was encased in concrete of thickness t_1, the load intensity showed as,

$$P_c = \frac{F_c}{A_c} = \frac{m_c g}{A_c} = \frac{\rho_c V_c g}{A_c} = \frac{\rho_c t_1 g(d_2 + d_1)}{2d_1} \qquad A_c = \pi d_2 L \tag{5}$$

$$V_c = \frac{\pi(d_2^2 - d_1^2)L}{4} = \frac{\pi(d_2 + d_1)(d_2 - d_1)L}{4} = \pi t L(d_2 - d_1) \qquad d_2 - d_1 = 2t$$

(ii) Concrete Weight

$$W_c = m_c g = \rho_c V_c g = \frac{\pi L_1 \rho_c g(d_3^2 - d_2^2)}{4} \tag{6}$$

(iii) Earth Mass Weight

$$W_e = m_e g = \rho_e V_e g = \pi \rho_e g\left[h^2 L - \frac{d_2^2 L}{4} - \frac{(d_3^2 - d_2^2)L_1}{4}\right] \qquad V_e = \pi\left[h^2 L - \frac{d_2^2 L}{4} - \frac{(d_3^2 - d_2^2)L_1}{4}\right] \tag{7}$$

(iv) Weight of gas inside the pipe

$$m_n = \frac{PV_g}{ZRT} \qquad R = \sum \frac{m_i}{m_H} R_i, \quad m_i = n_i M_i \qquad W_n = m_n g \tag{8}$$

(v) Pipe Weight

$$W_p = m_p g = \rho_p V_p g = \frac{\pi L_3 \rho_p g(d_1^2 - d_2^2)}{4} \tag{9}$$

Subject to the tri-axial stress condition, the maximum shear stress is the greatest of the three values.

$$\tau_{1\max} = \left|\frac{\sigma_1 - \sigma_2}{2}\right| \; or \; \left|\frac{\sigma_2 - \sigma_3}{2}\right| \; or \; \left|\frac{\sigma_3 - \sigma_1}{2}\right|$$

$$\therefore \quad \tau_{1\max} = \left|\frac{\sigma_3 - \sigma_1}{2}\right| \tag{10}$$

Under uni-axial stress condition, $\sigma_2, \ \sigma_3 = 0$

$$\tau_{2\max} = \frac{\sigma_1}{2} \tag{11}$$

Temperature stress in the system is express as;

$$\begin{aligned} \sigma_T &= E\varepsilon = E\frac{\Delta L}{L} \\ &= E\frac{\alpha L \Delta T}{L} \\ &= E\alpha\Delta T \end{aligned} \tag{12}$$

Based on these analyses, the overall induced maximum shear stress in the pipe can be express as:

$$\begin{aligned} \tau_{\max} &= \tau_{1\max} - \tau_{2\max} \\ &= \frac{\sigma_3 - \sigma_1}{2} - \frac{\sigma_T}{2} \end{aligned} \tag{13}$$

Applying failure (yielding) analysis known as maximum shear stress theory. The theory is base on the assumption that the pipe will fail or yield when the maximum induced shear stress reaches a value equal to the sear stress at the instant of failure or yielding in a simple tension test. Hence the allowable shear stress in the pipe is given as,

$$\tau_{\max} = \frac{0.5\sigma_{ypt}}{FS} = \frac{\sigma_{ypt}}{2FS}$$

$$\therefore \frac{|\sigma_3 - \sigma_1|}{2} - \frac{\sigma_T}{2} = \frac{\sigma_{ypt}}{2FS}$$

$$\sigma_1 - \sigma_3 - \sigma_T = \frac{\sigma_{ypt}}{FS} \tag{14}$$

Substituting equations 1, 3, and 12 in equation 14 to determine the design wall thickness of the pipe :

$$\frac{Pd_1}{2t} - \frac{Pd_1 - P_{ext}(d_1 + t)}{d_1 + t/2} - \sigma_T = \frac{\sigma_{ypt}}{FS}$$

$$t^2\left[-2P_{ext} - \sigma_T - \frac{\sigma_{ypt}}{FS}\right] + t\left[-1.5Pd_1 + 2P_{ext}d_1 - 2\sigma_T d_1 - \frac{2\sigma_{ypt}}{FS}\right] + pd_1 = 0 \tag{15}$$

$$a = -2P_{ext} - \sigma_E - \frac{\sigma_{ypt}}{FS}$$

$$b = -1.5Pd_1 + 2P_{ext}d_1 - 2\sigma_T d_1 - \frac{\sigma_{ypt}}{FS}$$

$$c = Pd_1$$

$$\bar{t} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \qquad (16)$$

The expression for the determination of the point of maximum deflection :

$$x^2\left[\frac{R_1}{2} - \frac{W_C}{2} - \left(\frac{W_P + W_n}{2}\right) - \frac{W_e}{2}\right] - x\left[W_c L_1 + \frac{(W_P + W_n)L}{2} + W_e L_2\right] + A_1 = 0$$

$$a_1 = \frac{R_1}{2} - \frac{W_C}{2} - \left(\frac{W_P + W_n}{2}\right) - \frac{W_e}{2}$$

$$b_1 = W_c L_1 + \frac{(W_P + W_n)L}{2} + W_e L_2$$

$$c_1 = A_1 = \frac{L}{2}\left[R_1 - W_c + \frac{W_p + W_c}{2} - W_e\right] + \frac{L}{2}\left[L_1 W_e + L_2 W_e\right]$$

$$\bar{c} = \frac{-b_1 \pm \sqrt{b_1^2 - 4a_1 c_1}}{2a_1} \qquad (17)$$

The reaction at support A and B :

$$R_1 + R_2 = W_C + W_e + W_p + W_n$$

Taking a moment about point B

$$R_1 = \frac{W_C\left(\frac{2L - L}{2}\right) + (W_P + W_C)L/2 + W_e\bar{x}}{L} \qquad (18)$$

$$R_2 = (W_C + W_e + W_P + W_C) - R_1 \qquad (19)$$

The maximum deflection is express as:

$$y = \left[\frac{R_1\bar{C}^3}{6} - W_C\left(\frac{\bar{C}^2}{6} - \frac{L_1\bar{C}^2}{2}\right) - (W_p + W_n)\left(\frac{\bar{C}^2}{6} - \frac{L\bar{C}^2}{4}\right) - W_e\left(\frac{\bar{C}^2}{6} - \frac{L_2\bar{C}^2}{2}\right) + A_1\bar{C}\right] / EI \qquad (20)$$

The expression gives the bending moment at the point of maximum deflection;

$$M = R_1\overline{C} - W_C\left(\overline{C} - L_1\right) - \left(W_P + W_n\right)\left(\overline{C} - L/2\right) - W_e\left(\overline{C} - L_2\right) \qquad (21)$$

The restoring force, F, at the point, if maximum deflection was given as

$$Fy = M, \qquad F = M / y \qquad (22)$$

Computer Simulated Algorithm

The computational, algorithmic codings are as follows :

```
% COMPUTER SIMULATION FOR THE UPLIFT RESISTANCE OF GAS PIPELINES NETWORK

% SYSTEM (PRODUCTION DATA OF SHELL PETROLUEM DEVELOPMENT CORPORATION,AUGUST 2008)

% 1/ SIMULATION FOR PIPES PIPES OPTIMUM WALL THICKNESS

% IINITIALIZING

% UPSTREAM PRESSURE AT SOKU , P1(N/m2)

  P1=81*10^5;

  disp('UPSTREAM PRESSURE, P1=')

  fprintf('%20.6f\n', P1)

% DOWNSTREAM PRESSURE AT BONNY (N/M2)

  P2=63*10^5;

  disp('DOWNSTREAM PRESSURE, P1=')

  fprintf('%20.6f\n', P2)

% AVERAGE STREAM PRESSURE, P (N/m2)

  P=(2/3)*(P1^3-P2^3)/(P1^2-P2^2);

  disp('AVERAGE STREAM PRESSURE, P=')
```

```
   fprintf('%20.6f\n', P)
% ATMOSPHERIC PRESSURE, Patm (N/m2)
   Patm=1.03*19^5;
%  SOIL DENSITY (SANDY LOAM DS (kg/m3)
   DS=1940;
% DENSITY OF CONCRETE, DC (kg/m3)
   DC=2310;
% MILD STEEL PIPE DENSIY, DP (kg/m3)
   DP=7820;
% PIPE NOMINAL DIAMETER (36") (m)
   d1=0.9144;
   disp('PIPE NOMINAL DIAMETER, d1=')
   fprintf('%20.6f\n', d1)
% PIPE THICKNESS, t1 (m)
    for t1=0.1:0.01:0.17
%   t1=0.11;
   disp('PIPE NOMINAL THICKNESS, t1=')
   fprintf('%20.6f\n', t1)
% PIPE OUTER DIAMETER, d2 (m)
   d2=d1+2*t1;
   disp('PIPE OUTER DIAMETER, d2=')
   fprintf('%20.6f\n', P2)
```

```
% THICKNESS OF CONCRETE CASING, t2 (m)

  t2=0.015;

% TEMPERATURE DROP ALONG LINE, DT (k)

  DT=246;

% OUTER DIAMETER OF CONCRETE CASING, d3 (m)

  d3=d2+2*t2;

% PIPE LENGTH, L (m)

  L=116000;

  L1=(2/3)*L;

  L2=L-L1;

% BURIAL DEPTH OF THE PIPE FROM THE CENTRE LINE OF PIPE, h (m)

  h=100;

% YOUG'S MODULUS OF ELASTICITY FOR MILD STELL, E (N/m2)

  E=213*10^9;

% FACTOR OF SAFETY FOR THE SYSTEM, FS

  FS=1.5;

  disp('FACTOR OF SAFETY, FS=')

  fprintf('%20.6f\n', FS)

% LINEAR EXPANSIVITY FOR MILD STEEL, A (/K)

  A=4.03*10^(-8);

% YIELD STRESS FOR MILD STEEL, YS, (N/m2)

  YS=260*10^6;
```

```
% BULK FLOW TEMPERATURE, T (K)
   T=313;
% TEMPERATURE DIFFERENCE, DT (K)
   TD=246;
% FLOW COMPRESSIBILITY FACTOR, Z
   Z=1.241;
%GRAVITATIONAL ACCELERATION, g (m/s2)
   g=9.81;
% GENERAL GAS CONSTANT, R0 (J/kgK)
   R0=8314;
% CIRCUMFERENTIAL STREEE, CS1 (N/m2)
   CS1=(P*d1)/(2*t1);
   disp('CIRCUMFERENTIAL OR HOOP STRESS, C1=')
   fprintf('%20.6f\n', CS1)
% LONGITUDINAL STRSS, (N/m2)
   CS2=(P*d1)/(4*t1);
   disp('LONGITUDINAL STRESS, CS2=')
   fprintf('%20.6f\n', CS2)
% BEARING PRESSURE DUE TO THE EARTH MASS
% VOLUME OF EARTH MASS, Ve, (m3)
   Ve=(22/7)*((h^2*L)-((d2^2-d1^2)*L)/4-((d3^2-d2^2)*L1)/4);
% WEIGHT OF EARTH MASS, We (N)
```

```
   We=DS*Ve*g;
   disp('    We     ')
   fprintf('%20.6f\n', We)
% BEARING PRESSURE DUE TO THE EARTH MASS
   Pext=We/((22/7)*d3*L1+d2*(L-L1));
   disp('  Ptex    ')
   fprintf('%20.6f\n', Pext)
% RADIAL STRESS, CS3 (N/m2)
   CS3=((-P*d1)+Pext*(d1+t1))/(d1+t1);
   disp('RADIAL STRESS, CS3=')
   fprintf('%20.6f\n', CS3)
%   disp(' CS1     CS2       CS3')
%   fprintf('%20.6f\n', CS1, CS2, CS3)
% TEMPERATURE STRESS, CT (N/m2)
   CT=E*A*DT;
   disp('TEMPERATURE STRESS, DT=')
   fprintf('%20.6f\n', DT)
% TO CALCULATE THE DESIGN WALL THICKNESS OF THE PIPE FOR SAFE OPERATION
    a=-2*Pext*d1-CT-(YS/FS);
    b=-1.5*P*d1+2*Pext*d1-2*CT*d1-(YS/FS);
    c=P*d1;
%  TO CALCULATE THE DESIGN WALL THICKNESS OF THE PIPE FOR SAFE OPERATION,th(m)
```

```
    th1=(-b-(-b^2-(4*a*c))^(0.5))/(2*a);

    th2=(-b-(-b^2+(4*a*c))^(0.5))/(2*a);

    disp(' DESIGN WALL THICKNESS OF PIPE,  th1           th2')

    fprintf('%12.6f\n',th1  ,th2)

% SHELL AERAGE GAS COMPOSITION

    C1=0.869859; C2=0.054574; C3=0.020709; IC4=0.004507; NC4=0.006309;

    IC5=0.002178; NC5=0.000787; C6=0.004627; N2=0.000598; CO2=0.034843;

% MOLECULAR MASS OF THE GASEEOUS MIXTURE

   M1=16; M2=30; M3=44; IM4=54; NM4=54; IM5=72; NM5=72; M6=86;MN2=28; MCO2=44;

% AVERAGE MOLECULAR MASS OF THE GAS, M (kg/mol)


M=C1*M1+C2*M2+C3*M3+IC4*IM4+NC4*NM4+IC5*IM5+NC5*NM5+C6*M6+N2*MN2+CO2*MCO2;

   disp('GAS AVERAGE MOLECULAR MASS,       M             ')

   fprintf('%20.6f\n', M)

% AVERAGE GAS CONSTANT, R (J/kgK)

   R=R0/M;

   disp('AVERAGE GAS DENSITY,     R     ')

   fprintf('%20.6f\n', R)

% AVERAGE FLOW PRESSURE, P (N/m2)

   P=92/3*(P1^3-P2^3)/(P1^2-P2^2);

% PIPE WEIGHT, Wp (N)

   Wp=((22/7)*(d2^2-d1^2)*DP*L*g)/4;

   disp('PIPE WEIGHT, Wp=')
```

```
    fprintf('%20.6f\n', Wp)
% CONCRETE WEIGHT, Wc (N)
    Wc=((22/7)*(d3^2-d2^2)*DC*L1*g)/4;
    disp('CONCRETE WEIGHT, Wc')
    fprintf('%20.6f\n', Wc)
% VOLUME OF GAS IN THE PIPELINE, Vg (m3)
    Vg=((22/7)*d1^2)*L;
% WEIGHT OF GAS IN THE PIPELINE
    Wg=(P*Vg*g)/(Z*R*T);
    disp('WEIGHT OF GAS, Wg=')
    fprintf('%20.6f\n', P2)
%   disp('  Wp  Wc     We    Wg')
%   fprintf('%12.6f\n',Wp, Wc,We,Wg)
% SIMULATION FOR THE UPLIFT RESISTANCE OF THE PIPELINE, F (N)
% TO DETERMINE x(m) (C1, C2)
    R1=((Wc*(2*L-L1)/2)+((Wp+Wg)*L)/2+(We*C1))/L;
    C1=((L-L1)*(h-(d1/2))*((L-L1)/2)+(L1*(h-(d3/2))*((2*L-L1)/2)))/((L-L1)*(h-(d2/2))+L1*(h-(d3/2)));
    A1=Wc*((L^2/6)-((L1*L)/4))-(Wp+Wg)*(L^2/12)+We*(((C1*L)/2)-(L^2/3))-((R1*L^2)/6);
    R2=(We+Wp+Wc+Wg)-R1;
% DETERMINATION OF x-COORDINATE POINT x (m)
    a1=R1/2-Wc/2-((Wp+Wg)/2)-We/2;
    b1=((Wc*L1)/2)-(Wp+Wg)*(L/2)+We*(L-C1);
```

```
   c1=A1;

   x1=(-b1-(-b1^2-(4*a1*c1))^(0.5))/(2*a1);

   x2=(-b1-(+b1^2-(4*a1*c1))^(0.5))/(2*a1);

   disp(' CENTROIDAL POINT FROM THE LEFT OF THE STRUCTURE, x1, x2')

   fprintf('%12.6f\n',x1,x2)

% TO DETERMINE THE SYSTEM MOMENT OF INERTIA, I (m4)

   I=((22/7)*((16*h^4)-d1^4))/64;

   disp(' MOMENT OF INERTIA OF THE SYSTEM,         I      ')

   fprintf('%12.6f\n',I)

% TO DETERMINE THE MAXIMUM DEFLECTION OF THE SYSTEM, ymax

   ymax1=((((R1*x1^3)/6)-Wc*(((x1^3)/6)-((L1*x1^2)/2))-(Wp+Wg)*(((x1^3)/6)-((L*x1^2)/4))-
We*(((x1^3)/6)-((L*x1^2)/2))+(A1*x1))/(E*I*10^8);

   disp('MAXIMUM DEFLECTION--1,       ymax1         ')

   fprintf('%12.6f\n',ymax1)

   ymax2=((((R1*x2^3)/6)-Wc*(((x2^3)/6)-((L1*x2^2)/2))-(Wp+Wg)*(((x2^3)/6)-((L*x2^2)/4))-
We*(((x2^3)/6)-((L*x2^2)/2))+(A1*x2))/(E*I*10^8);

   disp('MAXIMUM DEFLECTION--2       ymax2         ')

   fprintf('%12.6f\n',ymax2)

% THE BENDING MOMENT AT THE POINT OF MAXIMUM DELECTION, MB, (Nm)

   MB1=R1*x1-Wc*(x1-(L1/2))-(Wp+Wg)*(x1-(L/2))-We*(x1-(L-C1));

   disp(' BENDING MOMENT--1, MB1, DEFLECTION--1,    ymax1, RESTORING FORCE--1    F1 ')

   F1=(MB1/ymax1);

   fprintf('%20.6f\n',MB1,ymax1,F1)
```

```
MB2=R1*x2-Wc*(x2-(L1/2))-(Wp+Wg)*(x2-(L/2))-We*(x2-(L-C1));

disp(' BENDING MOMENT--2, MB1, DEFLECTION--2,  ymax2, RESTORING FORCE--2    F2 ')

F2=(MB2/ymax2);

fprintf('%20.6f\n',MB2,ymax2,F2)

 end
```

Input Parameters to the Algorithmic Coding

The input parameters to the algorithmic coding are in the Tables below:

Table 1: Dimensionless Equivalent Lengths of Pipeline Fittings (Source: Fox and McDonald, 1981)

Fitting Type	Description	Equivalent Length
Globe valve	Fully open	350
Gate valve	Fully open	13
	¾ open	35
	½ open	160
	¼ open	900
Check valve		50-100
90° standard elbow		30
45° standard elbow		15
90° elbow	Long radius	20
90° street elbow		50
45° street elbow		26
Tee	Flow through run	20
	Flow through branch	60
Return bend	Close pattern	50

Table 2: Geometric, Configuration and Operational Data for The Case study Gas Pipelines

Line Length (km)	Diameter (m)	Manifolds	Dsign Pressure (bar)	Input/Output Pressure (bar)	Flow Capacity (m^3/s)	Operating temperature (^0C)
116	0.9122	1	100	81/63	1.8	40
Allowable pressure drop (bar)	Coated/Uncoated	Flow Reynolds number	Flow specific gravity	Buried/Surface	Compressibility factor	
20	Coated	4000	0.6978	Buried	1.279	
			Gas Composition			
C_1	C_2	C_3	IC_4	NC_4	IC_5	C_6
0.888	0.05423	0.02882	0.0072	0	0.0038	0.0018
C_7	N_2	CO_2				
0.0016	0.0002	0.0075				

Table 3: Shell Optimised Panhandle- A Operating Threshold

D(m)	P_1(bar)	P_2(bar)	ΔP_{opt}	Q_{opt}	L(Km)
36"(0.9144)	50	30	25.25735	1.9421	116
	64	48	20.4483	1.94198	
	81	63	17.64499	1.94198	
	110	80	15.896981	1.9952	
	130	100	10.2772	1.94225	
	150	125	11.51225	1.94212	
	170	140	12.061	1.942396	
43"(1.0922)	50	30	24.0942	2.7596	
	64	48	19.544	2.7599	
	81	63	16.9213	2.76033	
	110	80	14.6143	2.7603	
	130	100	13.36898	2.760479	
	150	125	12.27117	2.75995	
	170	140	11.68059	2.76296	
50"(1.27)	50	30	22.841763	3.69643	
	64	48	16.10848	3.69615	
	84	63	16.10844	3.696154	
	110	80	13.9212	3.69745	
	130	100	12.72155	3.695531	
	150	125	11.751408	3.696517	
	170	140	11.18122	3.697248	

4. Results and Discussions

The output results from the computer simulated algorithm are in Table 4a to 4c below. In the design process, the equivalent length of all the inline items along the gas pipeline was obtained from Table 1. The data in Table 2 and 3 are input to the computational, algorithmic coding. It represents the operating threshold of the producing company on the Natural gas pipeline network system.

Table 3 is the results of optimization work on the thesis titled, "Flow Optimization in Natural Gas Pipeline" [1]. Table 3 represents the operating threshold of the pipeline within a range of operating pressures and nominal pipe diameters. The results of this research work in Table 4a confirmed that the optimal power to drive the compressor was higher than the operational power at pipe nominal diameter of 36"(0.9144m) at operating upstream and downstream pressures of 50—30bar, 64—48bar and 81—63bar respectively. This development is seemly impracticable from the perspective of the economy of operation. At operating upstream and downstream pressures of 110—80bar, 130—100bar, 150==125bar and 170—140bar the optimal power requirement to drive the compressor is much lesser than the operational power required. At nominal pipe diameter of 36" (0.9144m) is recommended to rub the Shell natural gas pipeline at operating upstream and downstream pressure order the 81—63bar due to the inherent increased flow throughput and a better economy in compressors operation. At nominal pipe diameter of 43", (1.0922m) improvement in the economy of operation of the compressors was obtainable at upstream/downstream pressures of 110—80bar and above. The pipeline mechanical design concept is only practicable at nominal pipe thicknesses of 0.05 and 0.10m. There is also increased flow throughput much more above what obtains at 36" (0.9144m) pipe diameter. The same analysis for 43" 1.0922m) goes for 50" (1.27m) nominal pipe diameter except the flow throughput is much more significant. The design table provides data for stress, nominal pipe thickness, pipe design thickness, support placement during the installation of pipeline assets and facilities, other physical and geometric design features and the driving power for flowing fluid stream. This is to give room for flexibility in design, material selection and installation of gas pipeline assets and facilities.

5. Recommendation for Future Research

New generation of natural gas pipeline be designed and installed taking cognizance of all the prevailing stresses to select the right and cheaper materials outside iron and steel products.

6. Conclusion

Computational algorithmic coding had been developed to generate data for design, material selection and installation of gas pipeline network system applying the developed optimized Panhandle-A equation. It is believed that this will create flexibility in the mechanical design concepts of gas pipeline network system.

Table 4a-4c: Output Results of Shell Petroleum Development Company Operating Threshold Using Developed Optimized Panhandle-A Equation

(a) Pipe Diameter--36"(0.9144m)

In all cases of operational pressure drops, the operational throughput is 1.8m^3/s

Factor of Safety, FS=1.5

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferential (Hoop) Stress σ_1(MN/m²)	Longitudinal Stress σ_2(MN/m²)	Radial Stress σ_3(MN/m²)
116000	0.9144m/36"	0.1	0.186	50	30	40.833	37.34	18.67	232.9
		0.11	0.1822				16.97	8.486	94.77
		0.12	0.179				15.56	7.779	205.1
		0.13	0.1747				14.36	7.18	210.6
		0.14	0.1711				13.34	6.668	198.3
		0.15	0.1674				12.45	6.223	195.1
		0.16	0.1683				11.67	5.834	191.75
		0.17	0.1603				10.98	5.941	188.1

Temperature Stress σ_T(MN/m²)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m^3/s)	Optimal Pressure Drop ΔP_{opt} (N/m^2)	Supports Placement from Left X_1 (m)	X_2 (m)	Maximum Deflection y_{max} (m)	Maximum Bending Moment M_{max}x10^{14} (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
2.112	95.76	1.9421	25.25735	57988	91475	-2.6977	7.167	-3.338	4.905	3.6
2.112	94.77			57987	91455	-2.968	7.532	-3.338		
2.112	93.69			57986	91452	-2.6977	7.9031	-3.3381		
2.112	92.57			57985	91450	-2.6977	8.281	-3.338		
2.112	91.42			57984	91449	-2.6977	8.665	-3.3381		
2.112	90.25			57982	91447	-2.6977	9.0559	-3.338		
2.112	89.68			57952	91445	-2.6907	9.453	-3.338		
2.112	87.97			57981	91443	-2.6977	9.8568	-3.338		

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferential (Hoop) Stress σ_1(MN/m²)	Longitudinal Stress σ_2(MN/m²)	Radial Stress σ_3(MN/m²)
116000	0.9144m/36"	0.05	0.2018	64	48	56.88	51.56	25.78	231.4
		0.1	0.1841				25.78	12.89	210.9
		0.105	0.1822				24.55	12.28	209.1
		0.11	0.1803				23.43	11.72	207.2
		0.12	0.1765				21.48	10.74	203.7
		0.13	0.1728				19.82	9.934	200.3
		0.14	0.1691				18.41	9.2	196.94
		0.15	0.1655				17.19	8.592	193.74
		0.16	0.1618				16.11	8.955	190.6
		0.17	0.1583				15.16	7.582	187.6

Temperature Stress σ_T(MN/m²)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m^3/s)	Optimal Pressure Drop ΔP_{opt} (N/m^2)	Supports Placement from Left X_1 (m)	X_2 (m)	Maximum Deflection y_{max} (m)	Maximum Bending Moment M_{max}x10^{14} (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
2.112	88.87	1.94198	20.4483	57992	91461	-2.6981	6.916	-3.338	3.971	2.88
2.112	91.51			57887	91451	-2.6981	8.6429	-3.3381		1.5
2.112	91.2			57986	914450	-2.6981	8.825	-3.338		1.5
2.112	98.4			57986	91449	-2.6981	9.002	-3.3381		1.5
2.112	90.05			57985	91447	-2.6981	9.3789	-3.3381		1.5
2.112	89.15			57983	91445	-2.6981	9.7566	-3.338		1.5
2.112	88.21			57692	91443	-2.6981	1.104	-3.338		1.5
2.112	87.216			57981	91441	-2.6981	1.053	-3.338		1.5
2.112	86.199			57980	91439	-2.6981	1.0929	-3.338		1.5
2.112	85.17			57979	91437	-2.6981	1.133	-3.338		1.5

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferential (Hoop) Stress σ_1(MN/m²)	Longitudinal Stress σ_2(MN/m²)	Radial Stress σ_3(MN/m²)
116000	0.9144m/36")	0.05	0.202	81	63	72.375	66.186	33.1	229.8
		0.1	0.1822				33.1	16.54	209.4
		0.105	0.1803						
		0.11	0.1784						
		0.12	0.1746						
		0.13	0.1708						
		0.14	0.1671						
		0.15	0.1634						
		0.17	0.1562						

Temperature Stress σ_T(MN/m²)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m^3/s)	Optimal Pressure Drop ΔP_{opt} (N/m^2)	Supports Placement from Left X_1 (m)	X_2 (m)	Maximum Deflection y_{max} (m)	Maximum Bending Moment M_{max}x10^{14} (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
2.112	80.8	1.94198	17.64499	57990	91455	-2.699	8.435	3.338	3.427	3.24
2.112	87.13			57962	91446	-2.6994	10.16	3.338		
2.112				57981	91445	-2.6894	10.34	3.338		
2.112				57983	91444	-2.699	10.5	-3.33		
2.112				57933	91442	-2.699	10.91	-3.338		
2.112				57969	91440	-2.6985	11.27	-3.338		
2.112				57961	91443	-2.6985	11.66	-3.336		
2.112				57377	91436	-2.6985	12.05	-3.338		
2.112				57978	91132	-2.6985	12.83	-3.3385		
2.112										

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferential (Hoop) Stress σ_1(MN/m^2)	Longitudinal Stress σ_2(MN/m^2)	Radial Stress σ_3(MN/m^2)
116000	0.9144m/36"	0.05	0.1994	110	80	95.79	95.79	87.59	227.7
		0.1	0.1794				43.75	21.897	207.35
		0.105	0.1745				41.71	20.86	205.5
		0.11	0.1734				43.79	21.897	207.35
		0.12	0.1717				36.49	13.25	200.2
		0.13	0.1679				33.69	16.84	196.8
		0.14	0.1641				31.28	15.66	193.5
		0.15	0.1604				29.2	14.6	190.3
		0.16	0.1568				27.37	13.69	187.3
		0.17	0.1531				25.76	12.88	184.3

Temperature Stress σ_T(MN/m^2)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m^3/s)	Optimal Pressure Drop ΔP_{opt} (N/m^2)	Supports Placement from Left X_1 (m)	X_2 (m)	Maximum Deflection y_{max} (m)	Maximum Bending Moment M_{max}x10^{14} (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
2.112	68.98	1.9952	15.896981	57985	91441	-2.6996	12.554	-3.338	3.172	5.4
2.112	80.723			57981	91431	-2.6996	14.269	-3.338		
2.112	80.848			57979	91430	-2.6996	14.45	-3.338		
2.112	80.77			57980	91429	-2.6996	14.63	-3.338		
2.112	80.8			57978	91427	-2.6996	15.01	-3.338		
2.112	80.5			57977	91425	-2.6996	15.38	-3.339		
2.112	80.06			57976	91423	-2.6996	15.77	-3.339		
2.112	79.5			57976	91421	-2.6996	16.16	-3.339		
2.112	78.89			57975	91419	-2.6996	16.56	-3.339		
2.112	78.21			57973	91417	-2.6996	16.96	-3.339		

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferential (Hoop) Stress σ_1(MN/m^2)	Longitudinal Stress σ_2(MN/m^2)	Radial Stress σ_3(MN/m^2)
116000	0.9144m/36"	0.05	0.1972	130	100	115.65	105.8	52.88	225.8
		0.1	0.177				52.88	26.438	205.6
		0.105	0.1751				50.36	25.18	203.7
		0.11	0.1731				48.08	24.04	201.9
		0.12	0.1692				44.46	22.03	198.4
		0.13	0.1654				40.68	20.34	195.1
		0.14	0.1616				37.77	18.88	191.8
		0.15	0.1577				35.25	17.63	188.6
		0.16	0.1542				33.05	16.52	185.6
		0.17	0.1505				31.1	15.56	182.6

Temperature Stress σ_T(MN/m^2)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m^3/s)	Optimal Pressure Drop ΔP_{opt} (N/m^2)	Supports Placement from Left X_1 (m)	X_2 (m)	Maximum Deflection y_{max} (m)	Maximum Bending Moment M_{max}x10^{14} (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
2.112	58.96	1.94225	10.2772	57985	91441	-2.6951	1.067	-3.338	1.966	5.4
2.112	75.29			57981	91431	-2.6691	12.384	-3.338		
2.112	75.63			57979	91430	-2.6951	12.565	-3.338		
2.112	75.88			57980	91429	-2.6691	12.38	-3.338		
2.112	96.13			57978	91427	-2.6951	13.12	-3.338		
2.112	76.14			57977	91425	-2.6691	13.5	-3.338		
2.112	75.96			57976	91423	-2.6951	13.88	-3.338		
2.112	75.64			57976	91421	-2.6691	14.27	-3.338		
2.112	75.21			57976	91419	-2.6951	14.67	-3.338		
2.112	74.7			57973	91417	-2.6691	15.12	-3.338		

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferential (Hoop) Stress σ_1(MN/m^2)	Longitudinal Stress σ_2(MN/m^2)	Radial Stress σ_3(MN/m^2)
116000	0.9144m/36"	0.05	0.1947	150	125	137.87	126.1	63.04	245
		0.1	0.1743				60.4	31.52	223.6
		0.11	0.1714				57.31	28.65	201.6
		0.12	0.1665				52.53	26.27	199.96
		0.13	0.1627				48.49	24.25	193.1
		0.14	0.1588				45.43	22.51	189.9
		0.15	0.1551				42.03	21.01	186.7
		0.16	0.1514				39.4	19.7	184
		0.17	0.1474				37.08	18.54	180.7

Temperature Stress σ_T(MN/m^2)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m^3/s)	Optimal Pressure Drop ΔP_{opt} (N/m^2)	Supports Placement from Left X_1 (m)	X_2 (m)	Maximum Deflection y_{max} (m)	Maximum Bending Moment M_{max}x10^{14} (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
2.112	47.75	1.94212	11.51225	57983	91423	-2.7001	1.465	-3.3383	2.236	4.5
2.112	69.2			57978	91424	-2.7001	1.639	-3.3385		
2.112	70.27			57977	91422	-2.7001	1.675	-3.3386		
2.112	70.92			57976	91420	-2.7001	1.7115	-3.3386		
2.112	71.26			57975	91418	-2.7002	1.749	-3.3386		
2.112	71.37			57974	91416	-2.7002	1.7877	-3.3387		
2.112	71.3			57973	91414	-2.7002	1.827	-3.3387		
2.112	71.09			57972	91412	-2.7002	1.867	-3.3388		
2.112	70.77			57971	91410	-2.7002	1.907	-3.3388		

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferential (Hoop) Stress σ_1(MN/m^2)	Longitudinal Stress σ_2(MN/m^2)	Radial Stress σ_3(MN/m^2)
116000	0.9144m/36"	0.05	0.1947	170	130	137.88	126.1	63.04	223.7
		0.1	0.1743				63.04	31.52	203.6
		0.11	0.1704				57.31	28.55	199.95
		0.12	0.1665				52.53	26.27	196.5
		0.13	0.1627				48.49	24.25	193.1
		0.14	0.1588				45.03	22.51	189.9
		0.15	0.1551				42.03	21.01	186.7
		0.16	0.1537				39.4	19.7	183.7
		0.17	0.1476				37.08	18.5	180.7

Temperature Stress σ_T(MN/m^2)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m^3/s)	Optimal Pressure Drop ΔP_{opt} (N/m^2)	Supports Placement from Left X_1 (m)	X_2 (m)	Maximum Deflection y_{max} (m)	Maximum Bending Moment M_{max}x10^{14} (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
2.112	22.37	1.942396	12.016	57983	91423	-2.7002	14.65	-3.3388	2.334	2.343
2.112	69.2			57978	91424	-2.7002	16.38	-3.3385		
2.112	70.27			57977	91422	-2.7001	16.74	-3.3386		
2.112	70.92			57976	91420	-2.7001	17.12	-3.3386		
2.112	71.26			57975	91418	17.49	17.59	-3.3386		
2.112	71.37			57974	91416	17.88	1.7877	-3.3387		
2.112	71.29			57973	91414	18.27	1.827	-3.3387		
2.112	71.09			57972	91412	18.67	1.867	-3.3388		
2.112	70.77			57971	91410	19.67	1.907	-3.3388		

(b) Pipe Diameter--43"(1.0922m)

In all cases of operational pressure drops, the operational throughput is 1.8m^3/s

Factor of Safety, FS=1.5

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferrential (Hoop) Stress σ_1(MN/m²)	Longitudinal Stress σ_2(MN/m²)	Radial Stress σ_3(MN/m²)
116000	1.0922m/43")	0.05	0.2083	50	30	40.833	44.6	22.3	498.3
		0.1	0.1915				22.3	11.15	183.1
		0.11	0.5192/-0.0724				932.5	466.3	13.41
		0.12	0.5156/-0.078				854.8	427.4	12.11
		0.13	0.5620/-0.0842				739	394.5	10.86
		0.14	0.5083/-0.09				732.68	266.3	9.6664
		0.15	0.5047/-0.0998				683.83	341.9	8.522
		0.16	0.501/-0.1015				641.1	320.6	7.425
		0.17	0.4073/-0.107				603.39	301.7	6.374

Temperature Stress σ_T (MN/m²)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m³/s)	Optimal Pressure Drop ΔP_{opt} (N/m²)	Supports Placement from Left X_1 (m)	X_2 (m)	Maximum Deflection y_{max} (m)	Maximum Bending Moment $M_{max}x10^{14}$ (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
2.112	75.77	2.7596	24.0942	57189	91452	-2.6988	94.88	-3.3383	6.649	3.6
2.112	79.35			57984	91441	-2.6988	11.5	-3.3383		
2.112	-461			57982	91439	-2.6988	11.93	-3.3383		
2.112	.-422.4			57981	91437	-2.6988	12.36	-3.3384		
2.112	.394.15			57981	91435	-2.6989	12.79	-3.3384		
2.112	-362.6			57979	91432	-2.6989	13.23	-3.3385		
2.112	.338.7			57978	91430	-2.699	13.68	-3.3385		
2.112	-317.9			57977	91428	-2.699	13.14	-3.3385		
2.112	-299.54			57976	91426	-2.6988	14.6	-3.3386		

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferrential (Hoop) Stress σ_1(MN/m²)	Longitudinal Stress σ_2(MN/m²)	Radial Stress σ_3(MN/m²)
116000	1.0922m/43"	0.05	0.2018	64	48	56.88	51.56	25.78	231.4
		0.1	0.1841				25.78	12.89	210.9
		0.105	0.1822				24.55	12.28	209.1
		0.11	0.1803				23.43	11.72	207.2
		0.12	0.1765				21.48	10.74	203.7
		0.13	0.1728				19.82	9.934	200.3
		0.14	0.1691				18.41	9.2	196.94
		0.15	0.1655				17.19	8.592	193.74
		0.16	0.1618				16.11	8.955	190.6
		0.17	0.1583				15.16	7.582	187.6

Temperature Stress σ_T (MN/m²)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m³/s)	Optimal Pressure Drop ΔP_{opt} (N/m²)	Supports Placement from Left X_1 (m)	X_2 (m)	Maximum Deflection y_{max} (m)	Maximum Bending Moment $M_{max}x10^{14}$ (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
2.112	88.87	1.94198	20.4483	57992	91461	-2.6981	6.916	-3.338	5.453	2.88
2.112	91.51			57887	91451	-2.6981	8.6429	-3.3381		
2.112	91.2			57986	914450	-2.6981	8.825	-3.338		
2.112	98.4			57986	91449	-2.6981	9.002	-3.3381		
2.112	90.05			57985	91447	-2.6981	9.3789	-3.3381		
2.112	89.15			57983	91445	-2.6981	9.7566	-3.338		
2.112	88.21			57692	91443	-2.6981	1.104	-3.338		
2.112	87.216			57981	91441	-2.6981	1.053	-3.338		
2.112	86.199			57980	91439	-2.6981	1.0929	-3.338		
2.112	85.17			57979	91437	-2.6981	1.133	-3.338		

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferrential (Hoop) Stress σ_1(MN/m²)	Longitudinal Stress σ_2(MN/m²)	Radial Stress σ_3(MN/m²)
116000	1.0922m/43")	0.05	0.2041	81	63	72.375	79.15	39.52	195.3
		0.1	0.1871				39.52	19.78	182.2
		0.11	0.465				16.53	18.22	118.4

Temperature Stress σ_T (MN/m²)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m³/s)	Optimal Pressure Drop ΔP_{opt} (N/m²)	Supports Placement from Left X_1 (m)	X_2 (m)	Maximum Deflection y_{max} (m)	Maximum Bending Moment $M_{max}x10^{14}$ (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
2.112	57.06	2.76033	16.9213	57957	91443	-2.6994	13.699	-3.3384	4.671	3.24
2.112	69.28			57981	91433	-2.6994	13.669	-3.3384		
2.112	-88.667			57980	91431	-2.6993	14.09	-3.3382		

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferrential (Hoop) Stress σ_1(MN/m²)	Longitudinal Stress σ_2(MN/m²)	Radial Stress σ_3(MN/m²)
116000	1.0922m/43")	0.05	0.201	110	80	95.79	104.6	52.31	193
		0.1	0.1838				52.31	26.16	178.1
		0.11	0.3738				2188	1094	-216.3

Temperature Stress σ_T (MN/m²)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m³/s)	Optimal Pressure Drop ΔP_{opt} (N/m²)	Supports Placement from Left X_1 (m)	X_2 (m)	Maximum Deflection y_{max} (m)	Maximum Bending Moment M_{max}x10^{14} (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
2.112	43.15	2.7603	14.6143	57983	91432	-2.7002	14.83	-3.3383	4.034	5.4
2.112	61.83			57978	91422	-2.7003	16.84	-3.3385		
2.112	-1203			57977	91420	-2.7003	17.26	-3.3386		

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferrential (Hoop) Stress σ_1(MN/m²)	Longitudinal Stress σ_2(MN/m²)	Radial Stress σ_3(MN/m²)
116000	1.0922m/43")	0.05	0.1983	130	100	115.65	126.3	65.2	197
		0.1	0.181				63.16	31.58	176
		0.105	0.1712/-0.561				264.1	132.1	299.1

Temperature Stress σ_T (MN/m²)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m³/s)	Optimal Pressure Drop ΔP_{opt} (N/m²)	Supports Placement from Left X_1 (m)	X_2 (m)	Maximum Deflection y_{max} (m)	Maximum Bending Moment M_{max}x10^{14} (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
2.112	31.35	2.760479	13.36898	57985	91423	-2.701	17.52	-3.3387	3.691	5.4
2.112	55.49			57975	91412	-2.6691	19.53	-3.3387		
2.112	-147			57974	91410	-2.6951	19.95	-3.3385		

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferrential (Hoop) Stress σ_1(MN/m²)	Longitudinal Stress σ_2(MN/m²)	Radial Stress σ_3(MN/m²)
116000	1.0922m/43")	0.05	0.1954	150	125	137.87	150.6	75.3	189
		0.1	0.1779				75.3	17.65	174.2
		0.11	0.1714				3149	1574	-292.2

Temperature Stress σ_T (MN/m²)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m³/s)	Optimal Pressure Drop ΔP_{opt} (N/m²)	Supports Placement from Left X_1 (m)	X_2 (m)	Maximum Deflection y_{max} (m)	Maximum Bending Moment M_{max}x10^{14} (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
2.112	18.15	2.75995	12.27117	57977	91441	-2.7017	20.53	-3.3389	3.387	4.5
2.112	48.41			57972	91402	-2.702	22.54	-3.3389		
2.112	-1772			579771	91399	-2.7018	22.96	-3.3386		

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferrential (Hoop) Stress σ_1(MN/m²)	Longitudinal Stress σ_2(MN/m²)	Radial Stress σ_3(MN/m²)
116000	1.0922m/43")	0.05	0.193	170	130	137.88	169.8	84.91	187.3
		0.1	0.2754				64.91	42.41	172.1
		0.11	0.00309/-0.8205				3551	1775	-465.7

Temperature Stress σ_T (MN/m²)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m³/s)	Optimal Pressure Drop ΔP_{opt} (N/m²)	Supports Placement from Left X_1 (m)	X_2 (m)	Maximum Deflection y_{max} (m)	Maximum Bending Moment M_{max}x10^{14} (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
2.112	76.97	2.76296	11.68059	57974	91404	-2.7023	22.91	-3.3388	3.227	5.4
2.112	42.79			57969	91393	-2.702	24.93	-3.339		
2.112	-2009			57968	91404	-2.7024	25.34	-3.339		

c) Pipe Diameter--50"(1.27m)

In all cases of operational pressure drops, the operational throughput is 1.8m^3/s

Factor of Safety, FS=1.5

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferrential (Hoop) Stress σ_1(MN/m²)	Longitudinal Stress σ_2(MN/m²)	Radial Stress σ_3(MN/m²)
116000	1.27m/50")	0.05	0.2098	50	30	40.833	44.6	22.3	498.3
		0.1	0.1952				22.3	11.15	183.1
		0.11	0.5228/-0.1053				932.5	466.3	13.41

Temperature Stress σ_T (MN/m²)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m^3/s)	Optimal Pressure Drop ΔP_{opt} (N/m^2)	Supports Placement from Left X_1 (m)	X_2 (m)	Maximum Deflection y_{max} (m)	Maximum Bending Moment M_{max}x10^{14} (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
2.112	75.77	3.69643	22.841763	57189	91452	-2.6988	94.88	-3.3383	8.443	5.4
2.112	79.35			57984	91441	-2.6988	11.5	-3.3383		
2.112	-461			57982	91439	-2.6988	11.93	-3.3383		

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferrential (Hoop) Stress σ_1(MN/m²)	Longitudinal Stress σ_2(MN/m²)	Radial Stress σ_3(MN/m²)
116000	1.27m/50")	0.05	0.2018	64	48	56.88	51.56	25.78	231.4
		0.1	0.1841				25.78	12.89	210.9
		0.105	0.1822				24.55	12.28	209.1

Temperature Stress σ_T (MN/m²)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m^3/s)	Optimal Pressure Drop ΔP_{opt} (N/m^2)	Supports Placement from Left X_1 (m)	X_2 (m)	Maximum Deflection y_{max} (m)	Maximum Bending Moment M_{max}x10^{14} (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
2.112	88.87	3.69615	16.10848	57992	91461	-2.6981	6.916	-3.338	5.954	2.88
2.112	91.51			57887	91451	-2.6981	8.6429	-3.3381		
2.112	91.2			57986	914450	-2.6981	8.825	-3.338		
2.112	98.4									
2.112	90.05									
2.112	89.15									
2.112	88.21									
2.112	87.216									
2.112	86.199									
2.112	85.17									

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferrential (Hoop) Stress σ_1(MN/m²)	Longitudinal Stress σ_2(MN/m²)	Radial Stress σ_3(MN/m²)
116000	1.27m/50")	0.05	0.2041	81	63	72.375	79.15	39.52	195.3
		0.1	0.1871				39.52	19.78	182.2
		0.11	0.465				16.53	18.22	118.4

Temperature Stress σ_T (MN/m²)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m^3/s)	Optimal Pressure Drop ΔP_{opt} (N/m^2)	Supports Placement from Left X_1 (m)	X_2 (m)	Maximum Deflection y_{max} (m)	Maximum Bending Moment M_{max}x10^{14} (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
2.112	57.06	3.696154	16.10844	57957	91443	-2.6994	13.699	-3.3384	5.954	3.24
2.112	69.28			57981	91433	-2.6994	13.669	-3.3384		
2.112	-88.667			57980	91431	-2.6993	14.09	-3.3382		

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferential (Hoop) Stress σ_1(MN/m²)	Longitudinal Stress σ_2(MN/m²)	Radial Stress σ_3(MN/m²)
116000	1.27m/50")	0.05	0.201	110	80	95.79	104.6	52.31	193
		0.1	0.1838				52.31	26.16	178.1
		0.11	0.3738				2188	1094	-216.3

Temperature Stress σ_T (MN/m²)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m³/s)	Optimal Pressure Drop ΔP_{opt} (N/m²)	Supports Placement from Left		Maximum Deflection y_{max} (m)	Maximum Bending Moment M_{max}x10^{14} (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
				X_1 (m)	X_2 (m)					
2.112	43.15	3.69745	13.9212	57983	91432	-2.7002	14.83	-3.3383	5.147	5.4
2.112	61.83			57978	91422	-2.7003	16.84	-3.3385		
2.112	-1203			57977	91420	-2.7003	17.26	-3.3386		

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferential (Hoop) Stress σ_1(MN/m²)	Longitudinal Stress σ_2(MN/m²)	Radial Stress σ_3(MN/m²)
116000	1.27m/50")	0.05	0.1983	130	100	115.65	126.3	65.2	197
		0.1	0.181				63.16	31.58	176
		0.105	0.1712/-0.561				264.1	132.1	299.1

Temperature Stress σ_T (MN/m²)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m³/s)	Optimal Pressure Drop ΔP_{opt} (N/m²)	Supports Placement from Left		Maximum Deflection y_{max} (m)	Maximum Bending Moment M_{max}x10^{14} (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
				X_1 (m)	X_2 (m)					
2.112	31.35	3.695531	12.75155	57985	91423	-2.701	17.52	-3.3387	4.701	5.4
2.112	55.49			57975	91412	-2.6691	19.53	-3.3387		
2.112	-147			57974	91410	-2.6951	19.95	-3.3385		

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferential (Hoop) Stress σ_1(MN/m²)	Longitudinal Stress σ_2(MN/m²)	Radial Stress σ_3(MN/m²)
116000	1.27m/50")	0.05	0.1954	150	125	137.87	150.6	75.3	189
		0.1	0.1779				75.3	17.65	174.2
		0.11	0.1714				3149	1574	-292.2

Temperature Stress σ_T (MN/m²)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m³/s)	Optimal Pressure Drop ΔP_{opt} (N/m²)	Supports Placement from Left		Maximum Deflection y_{max} (m)	Maximum Bending Moment M_{max}x10^{14} (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
				X_1 (m)	X_2 (m)					
2.112	18.15	3.696517	11.751408	57977	91441	-2.7017	20.53	-3.3389	4.344	4.5
2.112	48.41			57972	91402	-2.702	22.54	-3.3389		
2.112	-1772			579771	91399	-2.7018	22.96	-3.3386		

Pipe Length L (m)	Pipe Diameter D (meters/inches)	Pipe Nominal Thickness t (m)	Pipe Design Thickness t_d (m)	Upsream Pressure P_1 (bar)	Downstream Pressure P_2 (bar)	Average Stream Pressure P_{ave} (bar)	Circumferential (Hoop) Stress σ_1(MN/m²)	Longitudinal Stress σ_2(MN/m²)	Radial Stress σ_3(MN/m²)
116000	1.27m/50")	0.05	0.1923	170	130	137.88	197.5	98.73	161.5
		0.1	0.1768/0.2217				98.73	49.37	150.2
		0.11	-0.1695				4129	2064	-495.8

Temperature Stress σ_T (MN/m²)	Maximum Shear Stress $\tau_{max}(MN/m^2)$	Optimal Flow Capacity Q_{opt} (m³/s)	Optimal Pressure Drop ΔP_{opt} (N/m²)	Supports Placement from Left		Maximum Deflection y_{max} (m)	Maximum Bending Moment M_{max}x10^{14} (Nm)	Restoring Force F x10^{17} (N)	Compressor Power (optimal) P_{opt}(MW)	Compressor Power (operational) P_{opr}(MW)
				X_1 (m)	X_2 (m)					
2.112	-19.05	3.697248	11.18122	57966	91376	-2.7044	30.612	-3.3392	4.134	5.4
2.112	24.69			57966	91364	-2.7046	32.92	-3.3394		
2.112	-19.05			57959	91362	-2.7046	33.395	-3.3395		

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