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MODIFIED PANHANDLE-B MODEL IN OPTIMIZATION OF GAS PIPELINE DESIGN

Shadrack Mathew Uzoma
Mechanical Engineering Department,
University of Port Harcourt Nigeria
E-mail: mathshadrack@yaho.com

Tobinson A. Briggs (Corresponding author)
Mechanical Engineering Department,
University of Port Harcourt Nigeria
E-mail: tobinson.briggs@uiport.edu.ng

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 a lack in an economy the operation of the inline compressors. The developed optimization models employed the Modified Panhandle-B equation as base the base equation. The fundamental Modified Panhandle-B equation is amenable to increased flow throughput and lower overall line pressure drop. The driving power of the flowing fluid stream was not economically viable at operating downstream/upstream pressures of 81bar/63bar and below. At operating downstream/upstream pressures of 110bar/80bar, the optimal compressor power was much lesser than the operational capability. This development was consistent even at downstream/upstream pressures of 170bar/140bar. The nominal pipe thickness for all practical design considerations was found to be between 0.03m and 0,10m. At nominal pipe thickness over 0.11m, the prevailing radial stress and the maximum shearing resistance changed sign even the pipe designed thickness. The researchers confirmed that at a nominal pipe thickness of 0.11m and above, the design parameters could not fit well for gas pipeline stress analysis. The generated design parameters in-cooperated placement of pipe supports to balance the upheaval resistance of the pipeline. To counteract the effect of the numerical values of the pipe deflection, bending moment and restoring forces were determined by the computational approach. The knowledge of the design parameters for the pipeline subject to diverse loading situations could culminate in the design of a new generation pipeline network system employing piping materials order than convectional iron and steel products. It is well established that iron and steel materials are prone to environmental attack, known as corrosion and pitting. The cost of the massive tonnage of iron and steel materials to install a gas pipeline is also incredible. Being fully equipped with an operating range of stresses and other design parameters, the race to develop materials that are more resilient, cheaper, lighter in weight and more environmentally friendly could commence.
Keywords: Modified Panhandle-B Equation; Downstream/Upstream Pressures; Nominal Pipe Thickness; Design Pipe Thickness; Compressor Power; Upheaval Resistance; Corrosion and Pitting;

1. Introduction

The research aimed at developing a design, installation, and operating parameters for gas pipelines employing the results of optimized Panhandle-B models. The optimized Panhandle-B model's findings, the so-called operating threshold as part of the computational results of the thesis titled "Flow Optimization in Natural Gas Pipeline [1].

A lot of gas equations, correlations, and optimization models had been developed for the operations, design, and installation of gas pipeline network systems. Modern gas equations for pressure-capacity assessment of gas pipeline system are Weymouth equation, Panhandle-A and modified Panhandle-B equation [1]. The 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 [1, 3, 4, 5].

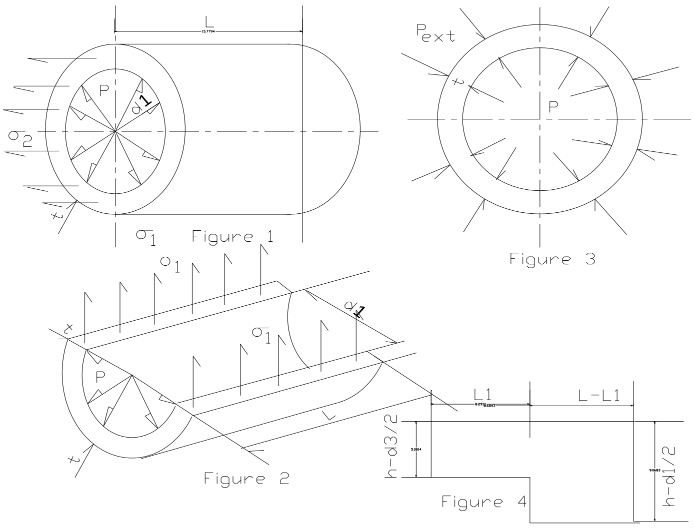
The developed flow optimization models were Doctor of Philosophy (Ph.D.) research work [1]. It has been extensively tested with operating and geometric data of five operating gas pipelines in Nigeria terrain. The methodology of the mechanical design concept was to work over a range of nominal pipe thickness to generate the designed wall thickness over a range of given upstream and downstream pressures. By computational approach, the prevailing stresses are it circumferential (hoop) stress, longitudinal stress, radial stress, and shearing resistance were determined. Parameters such as pipe support spacing, the maximum deflection, maximum bending moment, the restoring force were also determined by computationally. Optimal and operational power requirements were also calculated for the in-line compressor. The pipeline design concept is flexible enough to handle the gas pipeline design problem outside the range of functional and geometric data specified in this work.

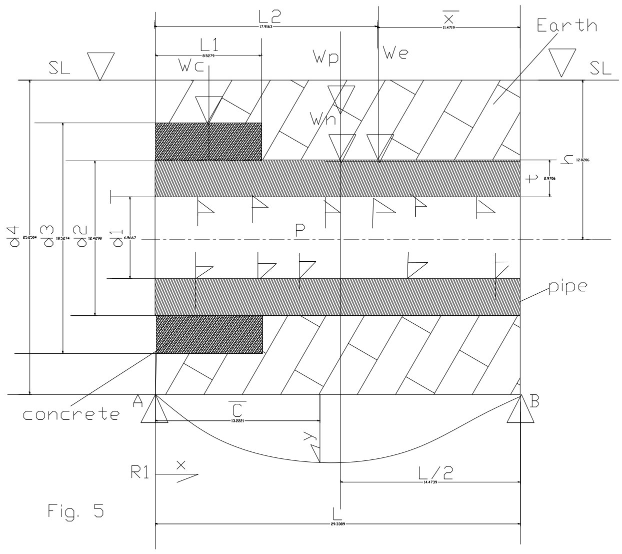
2. Study Significance

The significance is not far fetched from the fact that the generated design and operation parameters could be employed in developing a new generation of gas pipeline materials outside the traditional iron and steel products. The generated design parameters are worthy of emphasis. The parameters could aid in the selection of pipe materials knowing the prevailing stresses. Compressor sizing and spacing of pipe supports during installation is also 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 are formulated concerning stresses and load diagrams in Figures 1 to 5. [5]





Figures 1 to 5. Geometric representations for pipeline system on stress and uplift resistance computation (Source: Shadrack & Briggs [5])

Reinvoke the mathematical expression used by Shadrack and Briggs in their work [5]. The hoop or circumferential stress is express as :

$$\sigma_1 = \frac{Pd_1}{2t} \tag{1}$$

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

$$\sigma_2 = \frac{Pd_1}{4t} \tag{2}$$

The expression for the radial stress goes thus;

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

The resultant external load intensity on the structure is express as :

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

The different load components are designated as :

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

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

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

$$= \pi t L(d_2 - d_1)$$

$$d_2 - d_1 = 2t$$

(ii) Concrete Weight

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

(iii) Earth Mass Weight

$$W_e = m_e g = \rho_e V_e g$$

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

$$V_e = \pi \left[h^2 L - \frac{d_2^2 L}{4} - \frac{(d_3^2 - d_2^2)L_1}{4}\right]$$

(iv) Weight of gas inside the pipe

$$m_n = \frac{PV_g}{ZRT}$$

$$R = \sum \frac{m_i}{m_H} R_i, m_i = n_i M_i$$

$$W_n = m_n g \qquad (8)$$

(v) Pipe Weight

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

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

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

$$\therefore \tau_{1max} \left|\frac{\sigma_3 - \sigma_1}{2}\right| \qquad (10)$$

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

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

Temperature stress in the system is express as;

$$\sigma_T = E\varepsilon = E\frac{\Delta L}{L}$$

$$= E\frac{\alpha L \Delta T}{L}$$

$$= E\alpha\Delta T \tag{12}$$

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

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

Applying failure (yielding) analysis known as maximum shear stress theory. The theory is based 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 produced in a simple tension test [6, 7]. 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 equation14 to determine the design wall thickness of the pipe :

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

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

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

$$c = Pd_1$$

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

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

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

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

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

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

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

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

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

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

The maximum deflection is express as:

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

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

$$M = R_1\bar{C} - W_C(\bar{C} - L_1) - (W_P + W_n)(\bar{C} - L/2) - W_e(\bar{C} - L_2) \quad (21)$$

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

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

4. Computer Simulated Algorithm

The computational, algorithmic codings are as follows:

```
%   COMPUTER SIMULATION FOR THE UPLIFT RESISTANCE OF GAS PIPELINES NETWORK
%   SYSTEM (PRODUCTION DATA OF AN OIL PRODUCING COMPANY 2008)
%   SIMULATION FOR PIPES OPTIMUM WALL THICKNESS
%   IINITIALIZING
% UPSTREAM PRESSURE AT SOKU, P1(N/m2)
    P1=170*10^5;
    disp('UPSTREAM PRESSURE, P1=')
    fprintf('%20.6f\n', P1)
% DOWNSTREAM PRESSURE AT BONNY (N/M2)
    P2=140*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=1.27;
    disp('PIPE NOMINAL DIAMETER, d1=')
    fprintf('%20.6f\n', d1)
% PIPE THICKNESS, t1 (m)
     for t1=0.1:0.01:0.17
%       t1=0.05;
    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', d2)
% 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)
% Equivalent length of one globe valves, LEV(m)
   LEV=350*d1;
% Equivalent length of 13 globe valves
   LEVn=13*LEV;
% Equivalent length of one Tee-joint
% Flow through run
   LET1=20*d1;
% Flow through branch
   LET2=60*d1;
% Total effective length for 13 Tee-joint
   LETn=(13*(LET1+LET2));
% Line length, L(m)
  L=116000+(LEVn+LETn);
  disp('LINE LENGHT, L=')
  fprintf('%20.6f\n', L)
% L=116000;
% BURIAL DEPTH OF THE PIPE FROM THE CENTRE LINE OF PIPE, h (m)
    h=100;
% PIPE LENGTH, L1,    l2 (m)
    L1=(2/3)*L;
    L2=L-L1;
% 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, CT=')
    fprintf('%20.6f\n', CT)
%    MAXIMUM SHEARING RESISTANCE OF THE PIPE, SR (N/M2)
    SR=(CS3-CS1-CT)/2;
    disp('MAXIMUM SHEARING RESISTANCE, SR=')
    fprintf('%20.6f\n', SR)
% 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,th1th2')
      fprintf('%12.6f\n',th1,th2)
% SHELL AVERAGE 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
```

5. Input Parameters to The Algorithmic Coding

The input parameters to the algorithmic coding are in Tables 1 to 3 below.

6. 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 Tables 2 and 3 are input to the computational, algorithmic coding Table 2 is the results of optimization work on the thesis titled " Flow Optimization In Natural Gas Pipeline" [1, 8]. Table 2 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 4 confirmed that the optimal power to drive the compressor was more significant 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. The scenario is not much different at pipe diameters of 43” (1.0922m) and 50” (1,27m), respectively. The design analysis limits the nominal wall thickness of the pipe within 0.05m and 0.10m.

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 condition will give room for flexibility in design, material selection, and installation of gas pipeline assets and facilities.

7. Recommendation for Future Research

A new generation of the natural gas pipeline is designed and installed, taking cognizance of all the prevailing stresses to select the right type of materials outside iron and steel products. The material of interest should be resilient, cheaper, lighter in weight, and of longer service life compared to the conventional iron and steel materials.

8. Conclusion

The results of the operating threshold of optimized Panhandle-B were applied in the mechanical design of the gas pipeline network system. The design parameters were practical to the limits of pipe thickness in the range 0.05m to 0.10m, relation to compressor optimal and operational power requirement, the economy in the capital and operation costs of the compressor were arrived at between downstream-upstream pressures of 110bar/80bar to 170bar/140bar. At operating pressures of 81bar/63bar and below, the optimal compressor, power is much higher than the operational power requirement, hence creating a scenario of cost ineffectiveness in the capital and operation costs of the compressor. The mechanical design parameters are highly integrated computational design data providing valid information about pipe supports spacing, maximum pipe deflection, maximum bending moment, restoring force to avoid buckling of the pipeline under service conditions.

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Table 1: Dimensionless Equivalent Lengths of Pipeline Fittings

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

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Table 2: Geometric, Configuration and Operating Parameters for the Pipeline

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- B Operating Threshold

D(m)	P_1(bar)	P_2(bar)	ΔP_{opt}	Q_{opt}	L(Km)
36"(0.9144)	50	30	10.7459	2.692884	
	64	48	10.7514	2.69292	
	81	63	10.7511891	2.69292	
	110	80	10.75103	2.692901	
	130	100	10.751445	2.692948	
	150	125	10.548174	2.667838	
	170	140	10.750971	2.69289	
43"(1.0922)	50	30	10.54316	3.80743	
	64	48	10.514392	3.80743	
	81	63	10.514432	2.80744	
	110	80	10.51442	3.807436	
	130	100	10.51446	3.80446	
	150	125	10.514459	*3.807443*	
	170	140	10.51453	3.807456	
50"(1.27)	50	30	10.01172	5.03245	
	64	48	10.01172	5.032459	
	84	63	10.01175	5.033	
	110	80	10.01175	5.03246	
	130	100	10.011772	5.032463	
	150	125	10.011773	5.0324637	
	170	140	10.01177	5.032465	

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Table 4a-4c: Computational Output Results for the Gas pipeline

(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)	Circumferrential (Hoop) Stress σ_1(MN/m²)	Longitudinal Stress σ_2(MN/m²)	Radial Stress σ_3(MN/m²)
116000	0.9144m/36"	0.05	0.2109	50	30	40.833	37.34	18.67	239
		0.1	0.1915				18.67	9.335	217.9
		0.11	0.514/-0.0382				780.7	390.4	50.09

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	99.78	2.692884	10.7459	60548	95496	-3.2054	59.3	-3.0621	2.894	3.6
2.112	98.56			60542	95486	-3.2053	78.13	-3.062		
2.112	-3.664			60541	95483	-3.2053	82.1	-3.062		

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	0.9144m/36"	0.05	0.2092	64	48	56.88	51.56	25.778	237.5
		0.1	0.1897				25.78	12.89	216.5
		0.11	0.5048/-0.1174				1078	539	-13.8

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 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	11.94	2.69292	10.7514	60547	95490	-3.2059	7.539	-3.0621	2.895	2.88
2.112	94.3			60941	95480	-3.2058	9.421	-3.062		
2.112	-547			60539	95478	-3.2058	9.82	-3.062		

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	0.9144m/36")	0.05	0.202	81	63	72.375	66.18	33.09	229.9
		0.1	0.1822				33.09	16.55	209..5
		0.11	0.4841/-0.2179				1384	691.88	-81.49

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	80.8	2.69292	10.7511891	60545	95485	-3.2065	9.194	-3.062	3.165	3.24
2.112	87.13			69540	95475	-3.2065	11.68	-3.062		
2.112	-733.4			60539	95473	-3.2065	32.062	-3.062		

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	0.9144m/36"	0.05	0.1994	110	80	95.79	87.95	43.8	227.7
		0.1	0.1794				43.8	21.8	207.4
		0.11	0.4212/-0.349				183.14	915.7	-181.1

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	68.98	2.692901	10.75103	60543	95477	-3.2072	11.62	-3.062	2.895	5.4
2.112	86.72			60533	95467	-3.2072	15.499	-3.062		
2.112	-100.79			60536	95465	-3.2072	13.9	-3.062		

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	0.9144m/36"	0.05	0.1972	130	100	115.65	105.8	52.88	225.8
		0.1	0.177				52.88	16.44	205.6
		0.11	0.3469/-0.4601				221.1	110.6	262.6

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	58.9	2.692948	10.751445	60541	95470	-3.2078	13.672	-3.062	2.895	5.4
2.112	75.29			60535	95460	-3.2078	15.55	-3.063		
2.112	-123.8			60534	95458	-3.2078	15.95	-3.063		

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	0.9144m/36"	0.05	0.1947	150	125	137.87	126.1	63.04	123.9
		0.1	0.1743				630.4	31.52	203.6
		0.11	0.2445/-0.5845				265.6	13.83	353.9

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	47.75	2.667838	10.548174	60538	95462	-3.2085	15.97	-3.063	2.814	4.5
2.112	69.2			60533	95452	-3.2085	17.85	-3.063		
2.112	-1496			60532	95450	-3.2085	18.25	-3.063		

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	0.9144m/36"	0.05	0.1927	170	130	137.88	142.2	71.09	222
		0.1	0.1722				71.09	15.54	202
		0.11	0.1498/-0.683				29.73	148.6	-426.2

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	38.86	2.69289	10.750971	60336	95456	-3.209	17.79	-3.063	2.895	5.4
2.112	64.39			60531	95446	-3.209	19.68	-3.063		
2.112	-1700			60530	95443	-3.209	20.07	-3.063		

(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	198.3
		0.1	0.1915				22.3	11.15	183.1
		0.11	0.5192/.0.0724				93.25	466.3	13.41

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	75.79	3.80743	10.54316	61043	96273	-3.3127	52.2	-3.013	4.014	3.6
2.112	79.35			61038	96262	-3.3128	81.8	-3.013		
2.112	-460.6			61037	96260	-3.3128	10.41	-3.013		
							10.88			

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	0.2062	64	48	56.88	61.58	30.79	196.8
		0.1	0.1893				30.79	15.4	181.7
		0.11	0.5046/-0.1718				1288	643.8	-51.56

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	66.56	1.94198	20.4483	61041	96265	-3.3134	10.51	-3.013	5.394	2.88
2.112	74.39			61035	96254	-3.3135	12.75	-3.0123		
2.112	-670.6			61034	96252	-3.3135	13.21	-3.338		

(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	1.0922m/43")	0.05	0.2041	81	63	72.375	79.05	39.52	195.2
		0.1	0.1871				39.52	19.76	180.4
		0.11	0.5228/-0.1093				1084	542.2	-10.89
116000	1.27m/50")	0.05	0.2058	56	38	46.833	51.86	25.93	172.5
		0.1	[illegible]				[illegible]	[illegible]	[illegible]
		0.11	0.4649/-0.2782				1053	526.4	-118.2

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	39.27	5.03245	10.01172	[illegible]	[illegible]	-3.423	10.83	-2.964	5.03245	3.6
2.112	66.41			[illegible]	[illegible]	-3.4228	13.43	-2.964		
2.112	548.4			61530	97033	-3.4228	13.97	-2.964		
2.112	57.06	2.76033	19.9213	61039	96257	-3.3141	12.91	-3.012	5.499	3.24
2.112	6.929			61032	96246	-3.3142	15.15	-3.012		
2.112	-886.7			61032	96243	-3.3142	15.61	-3.013		

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	0.2074	64	48	56.88	71.6	35.8	171
		0.1	0.1927				35.8	17.9	159.4
		0.11	0.4338/-0.2211				1497	748.6	-76.21
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/-0.431				2188	1094	-21.63

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	48.65	5.032459	10.01172	61534	97037	-3.4236	14.04	-2.964	5.038	2.88
2.112	60.75			61528	97025	-3.4238	16.63	-2.965		
2.112	-787.8			61527	97022	-3.4238	17.17	-2.965		
2.112	43.15	2.7603	14.6143	61035	96245	-3.3151	16.43	-3.013	4.034	5.4
2.112	61.83			61029	96234	-3.3152	18.66	-3.013		
2.112	-1203			61029	96232	-3.3152	19.13	-3.013		

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	0.205	81	63	72.375	91.92	45.96	169.5
		0.1	0.1901				45.96	22.98	157.9
		0.11	0.4363/-0.1403				[illegible]	960.6	-143.9

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	37.72	5.033	10.01175	61531	97026	-3.4246	17.34	-2.964	5.039	3.24
2.112	54.93			[illegible]	97014	-3.4248	19.93	[illegible]		
2.112	-1034			[illegible]	97011	-3.4248	10.47	-1.949		

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	63.16	191.1
		0.1	0.181				63.15	31.58	176.2
		0.11	0.2712				2641	1321	-299.3
116000	1.27m (50")	0.05	0.2014	110	80	95.79	121.7	60.83	167.2
		0.1	0.1864				60.83	30.41	155.8
		0.11	0.3139				2544	1272	[illegible]

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	61932	96235	-3.316	19.41	-3.013	3.691	5.4
2.112	55.49			61026	96224	-3.316	21.64	-3.013		
2.112	-1470	5.03246	10.01175	61025	96221	-3.3161	22.44	-3.013	5.038	5.4
2.112	46.41			61520	96998	-3.4262	24.716	-2.965		
2.112	13.94			61519	96995	-3.4263	25.3	-2.965		

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	0.1984	130	100	115.65	146	73.44	165.3
		0.1	0.1832				73.44	36.72	153.9
		0.11	0.1797/-0.6627				3072	1536	-327.1
116000	1.0922m/43")	0.05	0.1954	150	125	137.87	150.6	75.3	189
		0.1	0.1779				75.3	37.65	174.2
		0.11	0.032/-0.7056				3149	1574	-392.2

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	8.161	5.032463	10.01172	61522	96996	-3.4272	26.26	-2.965	5.038	5.4
2.112	39.19			61516	96984	-3.4275	20.89	-2.965		
2.112	-1700			61515	96981	-3.4275	29.4	-2.965		
2.112	18.15	2.75995	12.27117	61108	96223	-3.317	22.74	-3.013	3.387	4.5
2.112	48.41			61023	96212	-3.3171	24.98	-3.014		
2.112	-1772			[illegible]	96210	-3.3171	25.44	-3.013		

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	0.195	150	125	137.87	175.1	87.55	163.2
		0.1	0.18				875.5	43.78	151.9
		0.11	-0.8293				3661	1831	-421.2

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	-70.23	5.0324637	10.01173	61507	96980	-3.4287	30.84	-2.965	5.038	4.5
2.112	31.1			61511	96968	-3.4289	33.44	-2.965		
2.112	-2042			[illegible]	96966	-3.4289	33.98	-2.965		

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	0.1754				84.91	42.46	172.6
		0.11	0.0039/-0.8205				3551	1775	-465.7
116000	1.27m/50")	0.05	0.1923	170	130	137.88	197.5	98.73	161.5
		0.1	[illegible]				98.73	[illegible]	[illegible]
		0.11	-0.9594				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 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	[illegible]	[illegible]	61026	996214	-3.3178	25.39	-3.013	[illegible]	[illegible]
2.112	42.8			61020	96203	-3.3176	27.62	-3.013		
2.112	-2009			61019	96201	-3.3199	28.09	-3.014		
2.112	19.05	5.032465	10.01177	61514	96968	-3.4198	34.47	-2.965	5.038	5.4
2.112	24.69			61508	96956	-3.4298	37.07	-2.965		
2.112	-2313			61506	96954	-3.43	37.608	-2.965		