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Optimization of Flow Parameters in Gas Pipeline Network System (Panhandle-A as Base Equation)

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ABSTRACT: *Gas pipeline assets and facilities are capital intensive production assets. Optimization of flow parameters in gas pipelines network system applying the models developed by the researcher is the focus of this work. The developed optimization models background is fundamental Panhandle A equation.*
The optimization results for single phase flow of gas in the five gas pipelines system used as case study confirmed that about 10% additional throughput over the normal operational levels could be accommodated by existing gas pipelines in Nigerian terrain. There could also be a drastic 20% to 45% reduction in line pressure drop.
It was discovered in this work that optimization of flow parameters led to drastic reduction in pressure drop along the line and increased flow throughput. It has been established that increased line pressure drop would ultimately lead increased pump and compressor power. As such, higher cost of design, construction and operation of gas pipeline should be the order of the day.
The developed optimization models for flow variables could enable gas pipeline assets and facilities to be designed and operated efficiently; so that our gas reserves could be conserved and deployed for strategic development ofthe nation's vast gas reserves estimated at 185 trillion standard cubic feet.
Keywords : *Assets and Facilities; Capital Intensive; Flow Parameters; Line Pressure Drop; Construction and Operation Costs; Strategic Development; Vast Gas Reserves; Criss-Crossing; Inefficiently Operated and Pipeline Network System.*

Nomenclature
V_L, V_G **– liquid and gas local velocities (m/s)**
$\bar{V}_M$ **–- mixture mean flow velocity (m/s)**
μ_G**—absolute gas viscosity (Pas)**
A, B, C—virialcoefficients (J/kg)

AR—area ratio
a—Van der Waals pressure correction factor (N/m^4)
b-- Van der Waals volume correction factor (m^3)
C—empirical constant

C_p**—ratio of static pressure to dynamic pressure**
d_0**—outside diameter of pipe (inches)**

D—nominal pipe diameter (cm)
d—pipe inner diameter (inches)
E—longitudinal weld joint factor

f_0**—friction factor for single phase flow**

f_{TP}**—Friction factor two phase flow**
G_{ave}**—average specific gravity of the mixture**

G—gas specific gravity
g—gravitational acceleration (m^2/s)
H_s**—hoop stress in pipe wall (psi)**

K_1, K_2, K_3**—constants**

K_4—entrance loss coefficient

K_5—exit loss coefficient

K_p—pump loss coefficient

K_w, K_{p1}, K_{p2}—constants
$\bar{V}_L,\ \bar{V}_G$ − **liquid and gas average velocities (m/s)**
$\partial^2 V_L / \partial n^2,\ \partial^2 V_G / \partial n^2$ − **liquid and gas acceleration gradients perpendicular to the axis of the pipe ($1/s^2$)**
$\partial V_L / \partial Z,\ \partial V_G / \partial Z$ − **liquid and gas velocity gradients along the axis of the pipe (1/s)**

L—length of pipeline (km)
m—mass of gaseous constituents (kg)

P_1—upstream pressure (bar)

P_2—downstream pressure (bar)

P_3—average flow pressure (bar)

P_b—base pressure (bar)

Q—flow capacity (m^3/s)
Q_g—gas flow rate (m^3/day)

Re_{NS}—Reynolds number at no slip condition
R—individual gas constant (J/kgK)
R_L, R_G—liquid and gas holdup
S—allowable yield stress for pipe (psi)
SG—specific gravity of the liquid relative to water
S_Y—maximum yield stress for pipe (psi)

T_b—base temperature (K)
T—bulk flow temperature (K)
T_{ol}—manufacturers tolerance allowance (m)
t—pipe wall thickness (inches)
t_{th}—thread or groove depth (inches)
V_g—gas velocity (ft/s)
V—mean flow velocity (m/s)
W—weight of pipe filled with water (lb/ft)
Y, F—derating factors
Z—flow compressibility factor

α_2—kinetic energy flux coefficient
λ—volume fraction of gas flowing (m^3/s)

μ_{NS}—Absolute viscosity at no slip condition (Pas)
v_f—kinematics viscosity of the fluid stream (Pas)
ρ_G—gas density (kg/m^3)
ρ_L—liquid density (Kg/m^3)

ρ_{NS}—density at no slip condition (kg/m^3)
ρ_{TP}—density for two-phase flow (Kg/m^3)
ΔH—elevation above datum (m)

ΔP_a—acceleration pressure drop (bar)

ΔP_{ec}—losses due to enlargement and contraction (bar)

ΔP_e—elevation pressure drop (bar)

ΔP_{ent}—entrance losses (bar)

ΔP_{exit}—exit losses (bar)

ΔP_f—frictional pressure drop (bar)

ΔP_{ft}—fitting losses (bar)

ΔP—overall pressure drop along the line (bar)

ΔP_p—pump losses (bar)

ΔP_v—valve losses (bar)

I. INTRODUCTION

Gas pipeline pressure-flow problem are affected by varieties of factors notably frictional pressure drop and other pressure drops components. These problems inevitably result in the reduction of the operating efficiency of gas pipelines by virtue of reduction in the line throughput and increased pressure drop along the line. It has been established that increased pressure drop will ultimately lead to increased pump power as well as higher cost of design, construction and operations of gas pipelines.

Flow optimization could enable these assets to be put to optimal use throughout their design life. Current gas reserves in Nigeria are conservatively put at approximately 185 trillion standard cubic feet [1]. Therefore, it is imperative that gas facilities be designed and operated efficiently so that available resources could be conserved and deployed for strategic development of the nation's vast gas resources. To this effect, the researcher has developed optimization models employing Weymouth equation, Panhandle A equation and Modified Panhandle B as the fundamental base equation [2, 3, 4].

Study Significance

The developed optimization models is the first of its kind. Matlab is used in coding the programming algorithm. The programming algorithmic coding is the easy to handle type. It produces optimal results of flow variables in few iteration steps. It is strongly believed that the findings in this work could provide the base for further in-depth research in gas pipeline flow optimization. The focus should be more biased on optimization of flow capacity viz-a-viz the overall pressure drop along a gas pipeline.

Thus the following objectives are imperative of this work:

(i) Predictability of performance.

(ii) Efficient utilization and deployment of gas pipeline assets and facilities.

(iv) Design efficiency in sizing gas pipelines and associated equipment.

(v) Greater economy in the design and operation of gas pipelines.

(vi) Longer service life to gas pipelines.

Relevant Optimization Models

Friction factor for two phase flow is expressed as :

$$f_{TP} = \left[0.00140 + \frac{0.125}{\left(\rho_G \bar{V}_M D / \mu_G \right)^{0.32}} \right] \times \left[1 + \frac{-\ln\left(1 - R_L\right)}{S} \right] \quad (1)$$

$$\mu_G = \mu_{GHC} + \mu_{GN_2} + \mu_{GCO_2} + \mu_{GH_2S}$$

$$S = 1.281 - 0.478(-\ln\lambda) + 0.444(-\ln\lambda)^2 - 0.94(-\ln\lambda)^3 + 0.0843(-\ln\lambda)^4$$
$$\lambda = 1 - R_L$$
$$\lambda = R_G$$

The absolute gas viscosity for the mixture of the hydrocarbon constituents of the gas is expressed by [5] :

$$\mu_{GHC} = 1.02247\times10^{-5}\begin{bmatrix} 8.188\times10^{-3} - 6.15\times10^{-3}\log(\gamma_G) \\ + \left(1.709\times10^{-5} - 2.062\times10^{-6}\gamma_G\right)(1.8T + 0.27) \end{bmatrix}. \quad (2)$$

The absolute viscosity of nitrogen is given as:

$$\mu_{GN_2} = 1.02247\times10^{-5}\left[9.59\times10^{-3} + 8.48\times10^{-3}\log(\gamma_G)\right]n_{N_2} \quad (3)$$

The absolute viscosity of carbon dioxide expressed as:

$$\mu_{GCO_2} = 1.02247\times10^{-5}\left[6.24\times10^{-3} + 9.08\times10^{-3}\log(\gamma_G)\right]n_{CO_2} \quad (4)$$

Absolute viscosity of hydrogen sulphide is given as:

$$\mu_{GH_2S} = 1.02247\times10^{-5}\left[3.73\times10^{-3} + 8.49\times10^{-3}\log(\gamma_G)\right]n_{H_2S} \quad (5)$$

Model for pressure drops along pump and compressor :

$$\Delta P_P = \frac{16\rho(1-\eta_i)}{\pi^2 d^4}Q^2$$
$$= K_P Q^2 \quad (6)$$
$$where \quad K_P = \frac{16\rho(1-\eta_i)}{\pi^2 d^4}$$

K_p—Pump constant
η_i=85 % to 97.5 % for most pumps and compressors [6].
Apparentmolecular weight of natural gas on the basis of the mole fractions of thedifferent constituents is expressed as:

$$M_a = \sum_{i=1}^{N} n_i M_i \quad (7)$$

The gaseous mixture specific gravity is given as:

$$\gamma_G = \frac{M_a}{M_{air}}. \quad (8)$$

In terms of the pseudo reduced properties, the critical pressure of the gaseous mixture is expressed as:

$$P_c = \sum_{i=1}^{N} n_i P_{Ci} \quad (9)$$

The critical temperature of the mixture is given as:

$$T_C = \sum_{i=1}^{N} n_i T_{Ci} \quad (10)$$

The reduced pressure and temperature are :

$$P_r = \frac{P}{P_C} \quad (11)$$

$$T_r = \frac{T}{T_C} \quad .(12)$$

Average gas pressure, P is given by [5] :

$$P = \frac{2}{3}\left(\frac{P_1^3 - P_2^3}{P_1^2 - P_2^2}\right) \quad (13)$$

Gas density is given as:

$$\rho_G = \frac{P}{ZRT} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(14)$$

OPTIMIZATION MODEL BASED ON PANHANDLE- A EQUATION

The fundamental Panhandle -A equation is expressed as [7] :

$$Q = K_{PA}\left(\frac{T_b}{P_b}\right)^{1.788}\left(\frac{1}{f}\right)^{0.5394}\left[\frac{P_1^2 - P_2^2}{\bar{T}ZL}\right]^{0.5394}\left(\frac{1}{G}\right)^{0.4606} D^{2.6182} \quad (15)$$

As it is in Equation (15), $K_{PA} = 1.90826$; the unit of K_{PA} is

$m^3Km^{0.5394}/K^{0.5394}cm^{2.618}day$.

Conditions of Application

Panhandle-A flow equation is applicable at moderate flow rates for partially developed turbulent flows and for long transmission lines. Usually the pipe wall is smooth. The flow situation is steady state flow, annular with suspended liquid mists in a two phase flow problem. The range of pipe diameter is greater than twelve inches (12”). The flow situation is annular in nature.

Equation (15) could be re expressed as ;

$$Q = K_{PA}\left(\frac{T_b}{P_b}\right)^{1.788}\left(\frac{1}{f}\right)^{0.5394}\left[\frac{(P_1 + P_2)(P_1 - P_2)}{\bar{T}ZL}\right]^{0.5394}\left(\frac{1}{G}\right)^{0.4606} D^{2.6182}$$

$$= K_{PA}\left(\frac{T_b}{P_b}\right)^{1.788}\left(\frac{1}{f}\right)^{0.5394}\left(\frac{1}{Z}\right)^{0.5394}\left[\frac{P_1 + P_2}{\bar{T}L}\right]^{0.5394}\left(\frac{1}{G}\right)^{0.4606} D^{2.6182}\Delta P^{0.5394}. \quad (16)$$

$\Delta P = P_1 - P_2$

In Equation 3.43, $K_{PA} = 1.90826$; the unit of K_{PA} is

$m^3Km^{0.5394}/K^{0.5394}cm^{2.618}day$.

Most gas transmission and transportation lines operate at high pressures and flow capacities. Consequently compressibility is a factor that must be given careful consideration in the evaluation of gas flow conditions in such pipelines. The compressibility factor Z, is determined from the gas compressibility equation which is a modification of ideal gas equation of state.

$$Q = K_{PA}\left(\frac{T_b}{P_b}\right)^{1.788}\left(\frac{1}{Z}\right)^{0.5394}\left(\frac{1}{G}\right)^{0.4606}\left[\frac{P_1+P_2}{\bar{T}L}\right]^{0.5394} D^{2.6182}\left(\frac{1}{f}\right)^{0.5394} \Delta P^{0.5394} \qquad (17)$$

$$\left(\frac{1}{Z}\right)^{0.5394} = \left[\frac{3\rho R_0 T(P_1+P_2)}{2\bar{M}(P_1^2+P_2^2+P_1P_2)}\right]^{0.5394}$$

$$\left(\frac{1}{G}\right)^{0.4606} = \left(\frac{M_a Z}{M}\right)^{0.4606}$$

$$\left(\frac{1}{G}\right)^{0.4606}\times\left(\frac{1}{Z}\right)^{0.5394} = \left(\frac{M_a Z}{M}\right)^{0.4606}\times\left(\frac{1}{Z}\right)^{0.5394} = \left(\frac{M_a}{M}\right)^{0.4606} Z^{-0.0788}$$

$$= \left(\frac{M_a}{M}\right)^{0.4606}\left[\frac{2\bar{M}(P_1^2+P_2^2+P_1P_2)}{3\rho R_0 T(P_1+P_2)}\right]^{-0.0788}$$

$$= 1.03247\left(\frac{M_a}{M}\right)^{0.4606}\left[\frac{\rho R_0 T(P_1+P_2)}{\bar{M}(P_1^2+P_2^2+P_1P_2)}\right]^{0.0788}$$

$$Q = K_{PA}\left(\frac{T_b}{P_b}\right)^{1.788}\left(\frac{1}{Z}\right)^{0.5394}\left(\frac{1}{G}\right)^{0.4606}\left[\frac{P_1+P_2}{\bar{T}L}\right]^{0.5394} D^{2.6182}\left(\frac{1}{f}\right)^{0.5394} \Delta P^{0.5394}$$

$$= 1.5^{0..0788} K_{PA}\left(\frac{T_b}{P_b}\right)^{1.788}\left(\frac{M_a}{\bar{M}}\right)^{0.4606}\left[\frac{\rho R_0 T(P_1+P_2)}{\bar{M}(P_1^2+P_2^2+P_1P_2)}\right]^{0.0788}\left[\frac{P_1+P_2}{\bar{T}L}\right]^{0.5394} D^{2.6182}\left(\frac{1}{f}\right)^{0.5394}\Delta P^{0.5394}$$

$$Q = K_{1PA}\left(\frac{1}{f}\right)^{0.5394}\Delta P^{0.5394} \qquad (18)$$

Where,

$$K_{1PA} = 1.5^{0..0788} K_{PA}\left(\frac{T_b}{P_b}\right)^{1.788}\left(\frac{M_a}{\bar{M}}\right)^{0.4606}\left[\frac{\rho R_0 T(P_1+P_2)}{\bar{M}(P_1^2+P_2^2+P_1P_2)}\right]^{0.0788}\left[\frac{P_1+P_2}{\bar{T}L}\right]^{0.5394} D^{2.6182}$$

The various pressure drop components in terms of the flow capacity are as follows [5] :

(a) Frictional Pressure Drop, ΔP_f

$$\Delta P_f = f\rho\frac{L}{D}\frac{V^2}{2} = \frac{8\rho L Q^2}{\pi^2 D^5} f = \frac{8\rho L Q^2}{\pi^2 D^5}\left[\frac{0.0014(\rho Q)^{0,32} + 0.1157(D\mu_G)^{0.32}}{(\rho Q)^{0,32}}\right]$$

$$= \frac{1}{\pi^2 D^5}\left[0.0112\rho L Q^2 + 0.9256\rho L(D\mu_G)^{0.322}\left(Q^2/\rho^{0.32}Q^{0.32}\right)\right]$$

$$= \frac{1}{\pi^2 D^5}\left[0.0112\rho L Q^2 + 0.9256\rho^{0.68}L(D\mu_G)^{0.32}Q^{1.68}\right]$$

$$L = L_L + L_{ev} + L_{ef} + L_{el}$$

Where:

L—overall length of pipeline (km)

L_L—length of pipe line based on required number of pipes (km)

L_{ev}—equivalent length of valves (km)

L_{ef}—equivalent length of fittings (km)

L_{el}—equivalent length of elbows (km)

(b) Elevation Pressure Drop, ΔP_e

$$\Delta P_e = \rho g \Delta H$$

(c) Entrance Losses (Pressure Drop), ΔP_{en}

$$\Delta P_{en} = \rho\left(K_{41} + \alpha_2 - 1\right)\frac{V^2}{2} = \frac{8\rho\left(K_{41} + \alpha_2 - 1\right)}{\pi^2 D^4} Q^2$$

(d) Exit losses (Pressure Drop), ΔP_{ex}

$$\Delta P_{ex} = K_{51}\frac{\rho V^2}{2} = \frac{8K_{51}\rho}{\pi^2 D^4} Q^2$$

(e) Pressure Drop Due To Enlargement and Contraction, ΔP_{ec}

$$\Delta P_{ec} = \frac{\rho V^2}{2}\left[\left(1 - \frac{1}{AR^2}\right) - C_P\right], \quad C_P = \frac{P_2 - P_1}{\rho V^2 / 2}$$

$$= \frac{\rho V^2}{2}\left[\left(1 - \frac{1}{AR^2}\right) + \frac{P_1 - P_2}{\rho V^2 / 2}\right]$$

$$= \frac{\rho V^2}{2}\left[\left(1 - \frac{1}{AR^2}\right) + \frac{\Delta P}{\rho V^2 / 2}\right]$$

$$= \left[\left(1 - \frac{1}{AR^2}\right)\frac{8\rho}{\pi^2 D^4} Q^2 + K^{-1/n} Q^{1/n}\right]$$

(f) Valves Pressure Drop, ΔP_v

$$\Delta P_V = f\rho\frac{L_{ev}}{D}\frac{V^2}{2} = \rho\frac{L_{ev}}{D}\frac{V^2}{2} f = \frac{8\rho L_{ev} Q^2}{\pi^2 D^5}\left[\frac{0.0014(\rho Q)^{0,32} + 0.1157(D\mu_G)^{0.32}}{(\rho Q)^{0,32}}\right]$$

$$= \frac{1}{\pi^2 D^5}\left[0.0112\rho L_{ev} Q^2 + 0.9256\rho L_{ev}(D\mu_G)^{0.322}\left(Q^2 / \rho^{0.32} Q^{0.32}\right)\right]$$

$$= \frac{1}{\pi^2 D^5}\left[0.0112\rho L_{ev} Q^2 + 0.9256\rho^{0.68} L_{ev}(D\mu_G)^{0.32} Q^{1.68}\right]$$

(g) Fittings Pressure Drop, ΔP_{ft}

$$\Delta P_{ft} = f\rho\frac{L_{ef}}{D}\frac{V^2}{2} = \rho\frac{L_{ef}}{D}\frac{V^2}{2} f = \frac{8\rho L_{ef} Q^2}{\pi^2 D^5}\left[\frac{0.0014(\rho Q)^{0,32} + 0.1157(D\mu_G)^{0.32}}{(\rho Q)^{0,32}}\right]$$

$$= \frac{1}{\pi^2 D^5}\left[0.0112\rho L_{ef} Q^2 + 0.9256\rho L_{ef}(D\mu_G)^{0.322}\left(Q^2 / \rho^{0.32} Q^{0.32}\right)\right]$$

$$= \frac{1}{\pi^2 D^5}\left[0.0112\rho L_{ef} Q^2 + 0.9256\rho^{0.68} L_{ef}(D\mu_G)^{0.32} Q^{1.68}\right]$$

The value assigned to L/D ratio either for the valves or fittings is a function of the type of valve or fitting in question.

(h) Acceleration Pressure Drop, ΔP_a

$$\Delta P_a = \frac{\rho V^2}{2} = \frac{8\rho}{\pi^2 D^4} Q^2$$

(i) Pump Pressure Drop, ΔPp

$$\Delta P_p = K_p Q^2, \qquad K_p = \frac{16\rho(1-\eta)}{\pi^2 D^4}$$

$$= \frac{16\rho(1-\eta)}{\pi^2 D^4} Q^2$$

The equation for pump pressure drop applies to all types of pumps and compressors, all that need be known is the isentropic efficiency of the particular pump or compressor.

(j) Overall Pressure Drop, ΔP is expressed as:

$$\Delta P = \Delta P_f + \Delta P_e + \Delta P_a + \Delta P_{en} + \Delta P_{ex} + \Delta P_{ec} + \Delta P_V + \Delta P_{ft} + \Delta P_p \qquad (19)$$

Substituting the various pressure drop components in Equation (3.46);

$$\Delta P = \begin{bmatrix} \frac{1}{\pi^2 D^5}\left[0.0112\rho L Q^2 + 0.9256\rho^{0.68} L\left(D\mu_G\right)^{0.32} Q^{1.68}\right] + \rho g \Delta H + \frac{8\rho}{\pi^2 D^4} Q^2 + \frac{8\rho\left(K_{41} + \alpha_2 - 1\right)}{\pi^2 D^4} Q^2 + \frac{8K_{51}\rho}{\pi^2 D^4} Q^2 + \\ \left(1 - \frac{1}{AR^2}\right)\frac{8\rho}{\pi^2 D^4} Q^2 + K^{-1/n} Q^{1/n} + \frac{1}{\pi^2 D^5}\left[0.0112\rho L_{ev} Q^2 + 0.9256\rho^{0.68} L_{ev}\left(D\mu_G\right)^{0.32} Q^{1.68}\right] + \\ \frac{1}{\pi^2 D^5}\left[0.0112\rho L_{ef} Q^2 + 0.9256\rho^{0.68} L_{ef}\left(D\mu_G\right)^{0.32} Q^{1.68}\right] + \frac{16\rho\left(1-\eta\right)}{\pi^2 D^4} Q^2 \end{bmatrix}$$

$$= \begin{pmatrix} \frac{0.0112\rho L}{\pi^2 D^5} Q^2 + \frac{8\rho}{\pi^2 D^4} Q^2 + \frac{8\rho\left(K_{41} + \alpha_2 - 1\right)}{\pi^2 D^4} Q^2 + \frac{8K_{51}\rho}{\pi^2 D^4} Q^2 + \\ \left(1 - \frac{1}{AR^2}\right)\frac{8\rho}{\pi^2 D^4} Q^2 + \frac{0.0112\rho L_{ev}}{\pi^2 D^5} Q^2 + \frac{0.0112\rho L_{ef}}{\pi^2 D^5} Q^2 + \frac{16\rho\left(1-\eta\right)}{\pi^2 D^4} Q^2 \end{pmatrix} +$$

$$\frac{1}{\pi^2 D^5}\left(0.9256\rho^{0.68} L\left(D\mu_G\right)^{0.32} + 0.9256\rho^{0.68} L_{ev}\left(D\mu_G\right)^{0.32} + 0.9256\rho^{0.68} L_{ef}\left(D\mu_G\right)^{0.32}\right) Q^{1.68}$$

$$+ K^{-1/n} Q^{1/n} + \rho g \Delta H$$

$$= \left[\frac{0.0112\rho L}{\pi^2 D^5} + \frac{8\rho}{\pi^2 D^4} + \frac{8\rho\left(K_{41} + \alpha_2 - 1\right)}{\pi^2 D^4} + \frac{8K_{51}\rho}{\pi^2 D^4} + \left(1 - \frac{1}{AR^2}\right)\frac{8\rho}{\pi^2 D^4} + \frac{0.0112\rho L_{ev}}{\pi^2 D^5} + \frac{0.0112\rho L_{ef}}{\pi^2 D^5} + \frac{16\rho\left(1-\eta\right)}{\pi^2 D^4}\right] Q^2$$

$$+ \left[\frac{1}{\pi^2 D^5}\left(0.9256\rho^{0.68} L\left(D\mu_G\right)^{0.32} + 0.9256\rho^{0.68} L_{ev}\left(D\mu_G\right)^{0.32} + 0.9256\rho^{0.68} L_{ef}\left(D\mu_G\right)^{0.32}\right)\right] Q^{1..68}$$

$$+ K^{-1/n} Q^{1/n} + \rho g \Delta H. \qquad (20)$$

Considering Equation (18), Panhandle-A exponent, n=0.5394 and $K=K_{1PA}(1/f)^{0.5394}$, therefore,

$$K^{-1/n} Q^{1/n} = \left(Q/K\right)^{1/n} = \left(Q/K\right)^{1/0.5394}$$

$$= \left[\frac{Q}{K_{1PA}\left(\frac{1}{f}\right)^{0.5394}}\right]^{1/0.5394} = \left[\frac{Qf^{\,0.5394}}{K_{1PA}}\right]^{1/0.5394}$$

$$= \frac{Q^{1.8539} f}{K_{1PA}^{1.8539}} = \frac{Q^{1.8539}}{K_{1PA}^{1.8539}}\left[0.0014 + \frac{0.1157\left(D\mu_G\right)^{0.32}}{\left(\rho Q\right)^{0,32}}\right]$$

$$= K_{1PA}^{-1.8539}\left[0.0014 Q^{1.8539} + 0.1157\left(\frac{D\mu_G}{\rho}\right)^{0.32} Q^{1.5339}\right]$$

$$= 0.0014 K_{1PA}^{-1.8539} Q^{1.8539} + 0.1157 K_{1PA}^{-1.8539}\left(\frac{D\mu_G}{\rho}\right)^{0.32} Q^{1.5339} \qquad (21)$$

Substituting Equation (3.48) in (3.47),

$$\Delta P = \left[\frac{0.0112\rho L}{\pi^2 D^5} + \frac{8\rho}{\pi^2 D^4} + \frac{8\rho\left(K_{41} + \alpha_2 - 1\right)}{\pi^2 D^4} + \frac{8K_{51}\rho}{\pi^2 D^4} + \left(1 - \frac{1}{AR^2}\right)\frac{8\rho}{\pi^2 D^4} + \frac{0.0112\rho L_{ev}}{\pi^2 D^5} + \frac{0.0112\rho L_{ef}}{\pi^2 D^5} + \frac{16\rho(1-\eta)}{\pi^2 D^4} \right] Q^2$$

$$+ \left[\frac{1}{\pi^2 D^5}\left(0.9256\rho^{0.68} L\left(D\mu_G\right)^{0.32} + 0.9256\rho^{0.68} L_{ev}\left(D\mu_G\right)^{0.32} + 0.9256\rho^{0.68} L_{ef}\left(D\mu_G\right)^{0.32} \right) \right] Q^{1..68}$$

$$+ K^{-1/n} Q^{1/n} + \rho g \Delta H$$

$$= \left[\frac{0.0112\rho L}{\pi^2 D^5} + \frac{8\rho}{\pi^2 D^4} + \frac{8\rho\left(K_{41} + \alpha_2 - 1\right)}{\pi^2 D^4} + \frac{8K_{51}\rho}{\pi^2 D^4} + \left(1 - \frac{1}{AR^2}\right)\frac{8\rho}{\pi^2 D^4} + \frac{0.0112\rho L_{ev}}{\pi^2 D^5} + \frac{0.0112\rho L_{ef}}{\pi^2 D^5} + \frac{16\rho(1-\eta)}{\pi^2 D^4} \right] Q^2$$

$$+ \left[\frac{1}{\pi^2 D^5}\left(0.9256\rho^{0.68} L\left(D\mu_G\right)^{0.32} + 0.9256\rho^{0.68} L_{ev}\left(D\mu_G\right)^{0.32} + 0.9256\rho^{0.68} L_{ef}\left(D\mu_G\right)^{0.32} \right) \right] Q^{1..68}$$

$$+ 0.0014 K_{1PA}^{-1.8539} Q^{1.8539} + 0.1157 K_{1PA}^{-1.8539} \left(\frac{D\mu_G}{\rho}\right)^{0.32} Q^{1.5339} + \rho g \Delta H$$

$$\Delta P = K_1 Q^2 + K_2 Q^{1.9608} + K_3 Q^{1.68} + K_4 Q^{1.6408} + \rho g \Delta H \qquad (22)$$

Where,

$$K_1 = \left[\frac{0.0112\rho L}{\pi^2 D^5} + \frac{8\rho}{\pi^2 D^4} + \frac{8\rho\left(K_{41} + \alpha_2 - 1\right)}{\pi^2 D^4} + \frac{8K_{51}\rho}{\pi^2 D^4} + \left(1 - \frac{1}{AR^2}\right)\frac{8\rho}{\pi^2 D^4} + \frac{0.0112\rho L_{ev}}{\pi^2 D^5} + \frac{0.0112\rho L_{ef}}{\pi^2 D^5} + \frac{16\rho(1-\eta)}{\pi^2 D^4} \right]$$

$$K_2 = 0.0014 K_{1PB}^{-1.9608}$$

$$K_3 = \left[\frac{1}{\pi^2 D^5}\left(0.9256\rho^{0.68} L\left(D\mu_G\right)^{0.32} + 0.9256\rho^{0.68} L_{ev}\left(D\mu_G\right)^{0.32} + 0.9256\rho^{0.68} L_{ef}\left(D\mu_G\right)^{0.32} \right) \right]$$

$$K_4 = 0.1157 K_{1PB}^{-1.9608} \left(\frac{D\mu_G}{\rho}\right)^{0.32}$$

Again making reference to Equation (18)

$$Q = K\Delta P^{0.5394} = K_{1PA}\left(\frac{1}{f}\right)^{0.5394} \Delta P^{0.5394} \tag{18}$$

$$= K_{1PA}\left(\frac{\Delta P}{f}\right)^{0.5394} = K_{1PA}\left[\frac{(\rho Q)^{0,32}\Delta P}{0.0014(\rho Q)^{0,32} + 0.1157(D\mu_G)^{0.32}}\right]^{0.5394}$$

$$= K_{1PA}\left[\frac{(\rho Q)^{0,32}\Delta P}{0.0014(\rho Q)^{0,32} + 0.1157(D\mu_G)^{0.32}}\right]^{0.5394}$$

$$1 = K_{1PA}\left[\frac{\dfrac{\Delta P(\rho Q)^{0,32}}{0.0014(\rho Q)^{0,32} + 0.1157(D\mu_G)^{0.32}}}{Q^{1/0.5394}}\right]^{0.5394} = K_{1PA}\left[\frac{\dfrac{\Delta P(\rho Q)^{0,32}}{0.0014(\rho Q)^{0,32} + 0.1157(D\mu_G)^{0.32}}}{Q^{1.8539}}\right]^{0.5394}$$

$$= K_{1PA}\left[\frac{\Delta P(\rho Q)^{0,32}Q^{-1.8539}}{0.0014(\rho Q)^{0,32} + 0.1157(D\mu_G)^{0.32}}\right]^{0.5394} = K_{1PA}\left[\frac{\rho^{0.32}Q^{-1.5339}\Delta P}{0.0014(\rho Q)^{0,32} + 0.1157(D\mu_G)^{0.32}}\right]^{0.5394}$$

$$= K_{1PA}\left[\frac{\rho^{0.32}Q^{-1.5339}\left(K_1Q^2 + K_2Q^{1.8539} + K_3Q^{1.68} + K_4Q^{1.5339} + \rho g\Delta H\right)}{0.0014(\rho Q)^{0,32} + 0.1157(D\mu_G)^{0.32}}\right]^{0.5394}$$

$$= K_{1PA}\left[\frac{\rho^{0.32}\left(K_1Q^{0.4661} + K_2Q^{0.32} + K_3Q^{0.1461} + K_4 + \rho g\Delta HQ^{-1.5339}\right)}{0.0014(\rho Q)^{0,32} + 0.1157(D\mu_G)^{0.32}}\right]^{0.5394}$$

$$K_{1PA}\left[\frac{\rho^{0.32}\left(K_1Q^{0.4661} + K_2Q^{0.32} + K_3Q^{0.1461} + K_4 + \rho g\Delta HQ^{-1.5339}\right)}{0.0014(\rho Q)^{0,32} + 0.1157(D\mu_G)^{0.32}}\right]^{0.5394} - 1 = 0$$

$$F(Q) = K_{1PA}\left[\frac{\rho^{0.32}\left(K_1Q^{0.4661} + K_2Q^{0.32} + K_3Q^{0.1461} + K_4 + \rho g\Delta HQ^{-1.5339}\right)}{0.0014(\rho Q)^{0,32} + 0.1157(D\mu_G)^{0.32}}\right]^{0.5394} - 1 \tag{23}$$

Differentiating the optimization function Equation (23) with respect to Q,

$$F(Q) = K_{1PA}\left[\frac{\rho^{0.32}\left(K_1Q^{0.4661} + K_2Q^{0.32} + K_3Q^{0.1461} + K_4 + \rho g\Delta HQ^{-1.5339}\right)}{0.0014(\rho Q)^{0,32} + 0.1157(D\mu_G)^{0.32}}\right]^{0.5394} - 1 \tag{23}$$

$$\frac{\partial F(Q)}{\partial Q} = K_{1PA}\rho^{0.32} n \left[\frac{\left(K_1 Q^{0.4661} + K_2 Q^{0.32} + K_3 Q^{0.1461} + K_4 + \rho g \Delta H Q^{-1.5339}\right)}{0.0014(\rho Q)^{0,32} + 0.1157\left(D\mu_G\right)^{0.32}} \right]^{n-1} \times$$

$$\frac{\left\{ \begin{array}{l} \left(0.0014(\rho Q)^{0,32} + 0.1157\left(D\mu_G\right)^{0.32}\right) \left(\begin{array}{l} 0.4661 K_1 Q^{-0.5339} + 0.32 K_2 Q^{-0.68} + 0.1461 K_3 Q^{-0,8539} + \\ -1.5339 \rho g \Delta H Q^{-2.5339} \end{array} \right) \\ -\left(\left(K_1 Q^{0.4661} + K_2 Q^{0.32} + K_3 Q^{0.1461} + K_4 + \rho g \Delta H Q^{-1.5339}\right)\right)\left(4.48 \times 10^{-4} \rho^{0.32} Q - 0.68\right) \end{array} \right\}}{\left(0.0014(\rho Q)^{0,32} + 0.1157\left(D\mu_G\right)^{0.32}\right)^2}$$

$$= K_{1PA}\rho^{0.32} n \left[\frac{\left(K_1 Q^{0.4661} + K_2 Q^{0.32} + K_3 Q^{0.1461} + K_4 + \left(D\mu_G\right)^{0.32} Q^{-1.5339}\right)}{0.0014(\rho Q)^{0,32} + 0.1157\left(D\mu_G\right)^{0.32}} \right]^{n-1} \times$$

$$\frac{\left\{ \begin{array}{l} 2.0454 \times 10^{-4} \rho^{0.32} K_1 Q^{-0.2139} + \left(0.0539\left(D\mu_G\right)^{0.32} - 2.4346 \times 10^{-4} \rho^{0.32} K_3\right) Q^{-0.5339} \\ + \left(0.037\left(D\mu_G\right)^{0.32} K_2 - 4.48 \times 10^{-4} \rho^{0.32}\right) Q^{-0.68} + 0.0169\left(D\mu_G\right)^{0.32} K_2 Q^{-0.8539} \\ + 0.1775\left(D\mu_G\right)^{0.32} \rho g \Delta H Q^{-2.5339} - 2.5955 \times 10^{-3} \rho^{0.32} \rho g \Delta H Q^{-2.5339} \end{array} \right\}}{\left(0.0014(\rho Q)^{0,32} + 0.1157\left(D\mu_G\right)^{0.32}\right)^2} \quad ..(24)$$

Differentiating Equation (24) twice with respect to Q

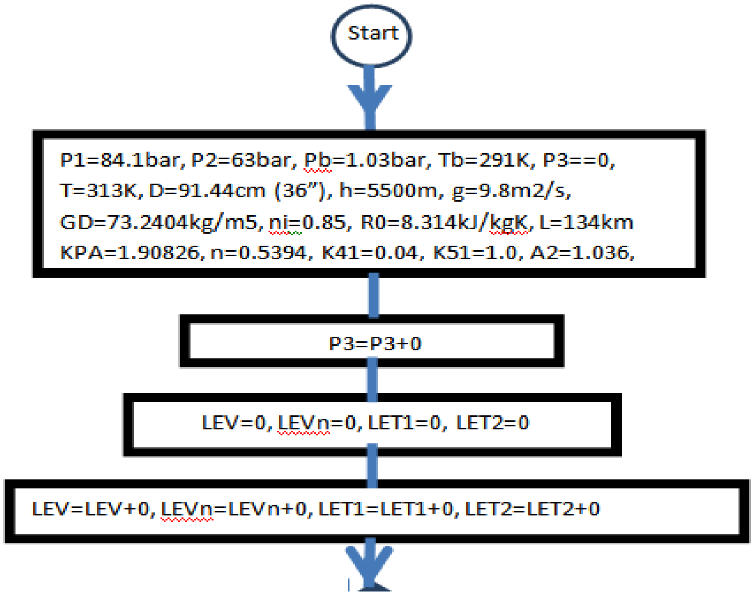
$$\frac{\partial F^2(Q)}{\partial Q^2} = K_{1PA}\rho^{0.32} n(n-1) \left[\frac{\left(K_1 Q^{0.4661} + K_2 Q^{0.32} + K_3 Q^{0.1461} + K_4 + \left(D\mu_G\right)^{0.32} Q^{-1.5339}\right)}{0.0014(\rho Q)^{0,32} + 0.1157\left(D\mu_G\right)^{0.32}} \right]^{n-2} \times$$

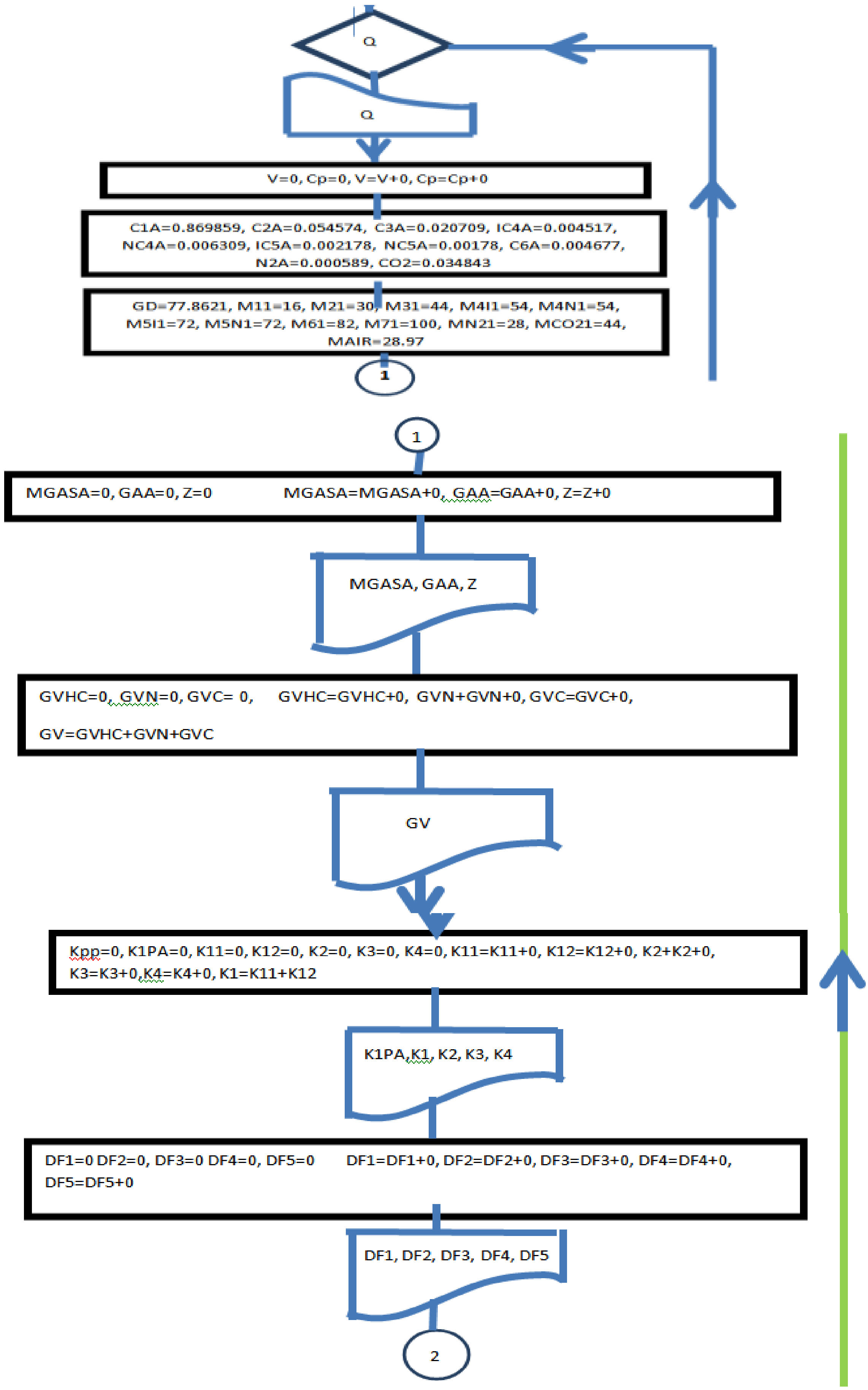
$$\left\{ \frac{ \begin{array}{l} 2.0454 \times 10^{-4} \rho^{0.32} K_1 Q^{-0.2139} + \left(0.0539\left(D\mu_G\right)^{0.32} - 2.4346 \times 10^{-4} \rho^{0.32} K_3\right) Q^{-0.5339} \\ + \left(0.037\left(D\mu_G\right)^{0.32} K_2 - 4.48 \times 10^{-4} \rho^{0.32}\right) Q^{-0.68} + 0.0169\left(D\mu_G\right)^{0.32} K_2 Q^{-0.8539} \\ + 0.1775\left(D\mu_G\right)^{0.32} \rho g \Delta H Q^{-2.5339} - 2.5955 \times 10^{-3} \rho^{0.32} \rho g \Delta H Q^{-2.5339} \end{array} }{\left(0.0014(\rho Q)^{0,32} + 0.1157\left(D\mu_G\right)^{0.32}\right)^2} \right\}^2$$

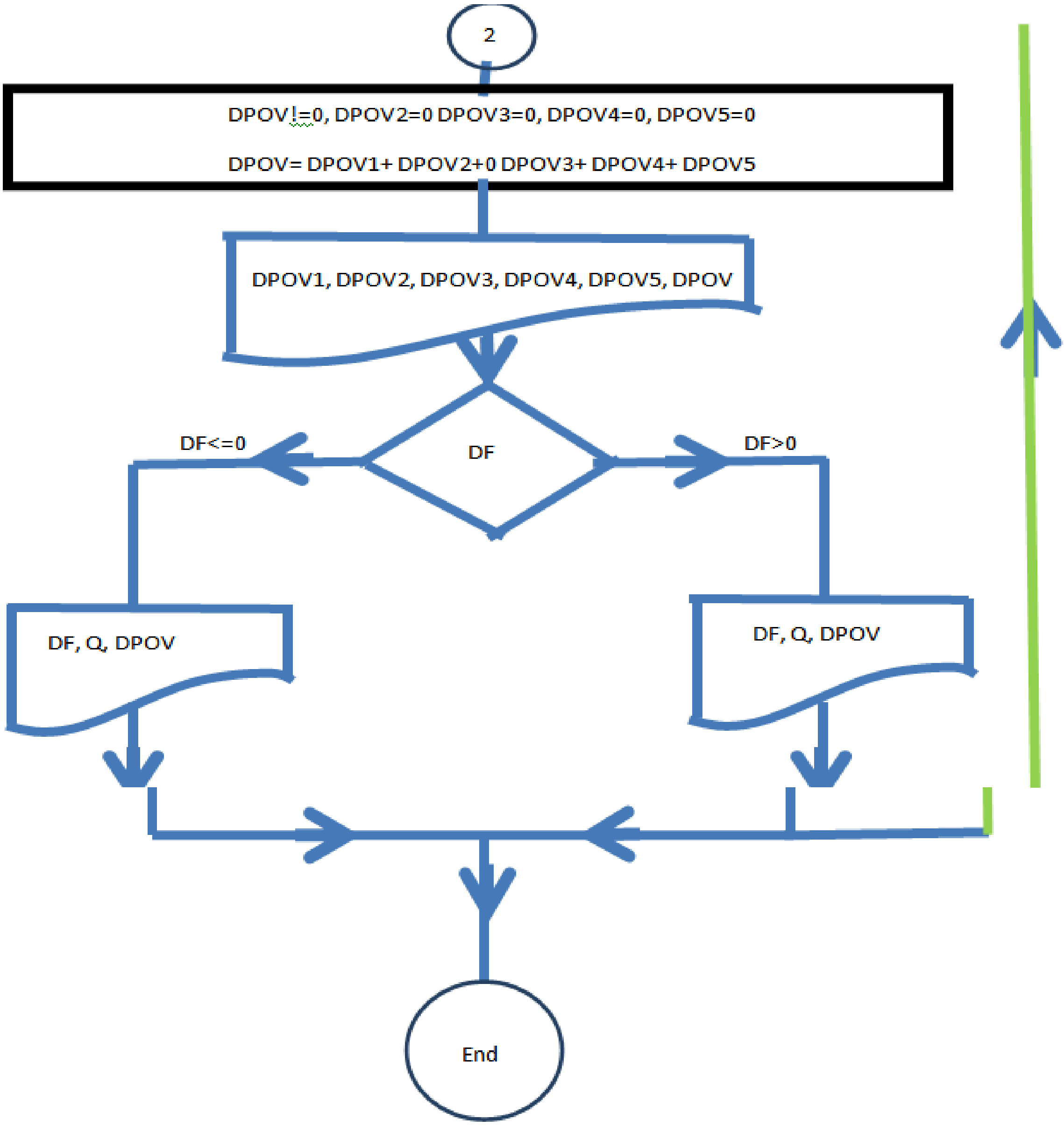
$$+K_{1PA}\rho^{0.32}n\left[\frac{\left(K_1Q^{0.4661}+K_2Q^{0.32}+K_3Q^{0.1461}+K_4+\rho g\Delta HQ^{-1.5339}\right)}{0.0014(\rho Q)^{0,32}+0.1157\left(D\mu_G\right)^{0.32}}\right]^{n-1}\times$$

$$\frac{\left\{\begin{array}{l}\left\{\left(0.0014(\rho Q)^{0,32}+0.1157\left(D\mu_G\right)^{0.32}\right)^2\right\}\left[\begin{array}{l}-4.3751\times10^{-5}\rho^{0.32}K_1Q^{-1.2139}\\-\left(1.3\times10^{-4}\rho^{0.32}K_3+0.02878\left(D\mu_G\right)^{0.32}\right)Q^{-1.5339}\\-\left(0.02516\left(D\mu_G\right)^{0.32}-3..0464\times10^{-4}\rho^{0.32}\right)Q^{-1.68}\\-0.0144\left(D\mu_G\right)^{0.32}K_2Q^{-1.8539}\\+0.005746\rho^{0.32}\rho g\Delta HQ^{-3.2139}\\-0.4498\left(D\mu_G\right)^{0.32}\rho g\Delta HQ^{-3.5339}\end{array}\right]-\\8.96\times10^{-4}\rho^{0.32}\left(0.0014(\rho Q)^{0,32}+0.1157\left(D\mu_G\right)^{0.32}\right)Q^{-0.68}\left\{\begin{array}{l}2.0454\times10^{-4}\rho^{0.32}K_1Q^{-0.2139}\\+\left(0.0539\left(D\mu_G\right)^{0.32}-2.4346\times10^{-4}\rho^{0.32}K_3\right)Q^{-0.5339}\\+\left(0.037\left(D\mu_G\right)^{0.32}K_2-4.48\times10^{-4}\rho^{0.32}\right)Q^{-0.68}\\+0.0169\left(D\mu_G\right)^{0.32}K_2Q^{-0.8539}\\+0.1775\left(D\mu_G\right)^{0.32}\rho g\Delta HQ^{-2.5339}\\-2.5955\times10^{-3}\rho^{0.32}\rho g\Delta HQ^{-2.5339}\end{array}\right\}\end{array}\right\}}{\left(0.0014(\rho Q)^{0,32}+0.1157\left(D\mu_G\right)^{0.32}\right)^4}\quad.....(25)$$

Flowchart for The Programing Algorithmic Coding




Q
Q
V=0, Cp=0, V=V+0, Cp=Cp+0
C1A=0.869859, C2A=0.054574, C3A=0.020709, IC4A=0.004517, NC4A=0.006309, IC5A=0.002178, NC5A=0.00178, C6A=0.004677, N2A=0.000589, CO2=0.034843
GD=77.8621, M11=16, M21=30, M31=44, M4I1=54, M4N1=54, M5I1=72, M5N1=72, M61=82, M71=100, MN21=28, MCO21=44, MAIR=28.97
1
1
MGASA=0, GAA=0, Z=0 MGASA=MGASA+0, GAA=GAA+0, Z=Z+0
MGASA, GAA, Z
GVHC=0, GVN=0, GVC= 0, GVHC=GVHC+0, GVN+GVN+0, GVC=GVC+0,
GV=GVHC+GVN+GVC
GV
Kpp=0, K1PA=0, K11=0, K12=0, K2=0, K3=0, K4=0, K11=K11+0, K12=K12+0, K2+K2+0,
K3=K3+0, K4=K4+0, K1=K11+K12
K1PA, K1, K2, K3, K4
DF1=0 DF2=0, DF3=0 DF4=0, DF5=0 DF1=DF1+0, DF2=DF2+0, DF3=DF3+0, DF4=DF4+0,
DF5=DF5+0
DF1, DF2, DF3, DF4, DF5
2



Input Parameters

Table 1: Geometric, Configuration and Operational Data for The Case study Gas Pipelines

<table>
<tr><td colspan="7">ElfTotal Nig. Ltd
Physical Configuration: From Obite to Bonny NLNG
Terrain transversed: From Obite to Ndele to Bonny NLNG
Design Standard Code: ANSI/ASME B31.8 Standard Code</td></tr>
<tr><td>Length(km)</td><td>Diameter(cm)</td><td>Manifolds</td><td>Design Pressure(bar)</td><td>Input/Output Pressure(bar)</td><td>Flow Rate(m^3/s</td><td>Operating Temperature (^{0}C)</td></tr>
<tr><td>134</td><td>36"(91.44cm)</td><td>2</td><td>100</td><td>84/63</td><td>1.8</td><td>40</td></tr>
<tr><td>Allowable Pressure Drop(bar)</td><td>Coated/ Uncoated</td><td>Flow Reynolds Number</td><td>Specific Gravity</td><td>Buried/Surface</td><td>Compressibility Factor</td><td></td></tr>
<tr><td>20</td><td>coated</td><td>4000</td><td>0.6657</td><td>Buried</td><td>0.749</td><td></td></tr>
<tr><td colspan="7">Shell Petroleum Development Company
Physical Configuration: From Soku to Bonny NLNG
Terrain transversed: From Soku to Ndele to Bonny NLNG
Design Standard Code: ANSI/ASME B31.8 Standard Code</td></tr>
<tr><td>Length(km)</td><td>Diameter(cm)</td><td>Manifolds</td><td>Design Pressure(bar)</td><td>Input/Output Pressure(bar)</td><td>Flow Rate(m^3/s</td><td>Operating Temperature (^{0}C)</td></tr>
<tr><td>116</td><td>36"(91.44cm)</td><td>1</td><td>100</td><td>81/63</td><td>1.8</td><td>40</td></tr>
<tr><td>Allowable Pressure Drop(bar)</td><td>Coated/ Uncoated</td><td>Flow Reynolds Number</td><td>Specific Gravity</td><td>Buried/Surface</td><td>Compressibility Factor</td><td></td></tr>
<tr><td>20</td><td>coated</td><td>4000</td><td>0.6978</td><td>Buried</td><td>1.273</td><td></td></tr>
<tr><td colspan="7">Agipl Nig. Ltd
Physical Configuration: From Obiafu to Bonny NLNG
Terrain transversed: From Obiafu to Bonny NLNG
Design Standard Code: ANSI/ASME B31.8 Standard Code</td></tr>
<tr><td>Length(km)</td><td>Diameter(cm)</td><td>Manifolds</td><td>Design Pressure(bar)</td><td>Input/Output Pressure(bar)</td><td>Flow Rate(m^3/s</td><td>Operating Temperature (^{0}C)</td></tr>
<tr><td>134</td><td>36"(91.44cm)</td><td>2</td><td>100</td><td>84/63</td><td>1.8</td><td>40</td></tr>
<tr><td>Allowable Pressure Drop(bar)</td><td>Coated/ Uncoated</td><td>Flow Reynolds Number</td><td>Specific Gravity</td><td>Buried/Surface</td><td>Compressibility Factor</td><td></td></tr>
<tr><td>20</td><td>coated</td><td>4000</td><td>0.6657</td><td>Buried</td><td>0.749</td><td></td></tr>
<tr><td colspan="7">Nigeria Gas Company (NGC) Eastern Division
Physical Configuration: From Warri to Okitipupa
Terrain transversed: From Ogharepe Warri to Okitipupa Ondo
Design Standard Code: ANSI/ASME B31.8 Standard Code</td></tr>
<tr><td>Length(km)</td><td>Diameter(cm)</td><td>Manifolds</td><td>Design Pressure(bar)</td><td>Input/Output Pressure(bar)</td><td>Flow Rate(m^3/s</td><td>Operating Temperature (^{0}C)</td></tr>
<tr><td>122</td><td>36"(91.44cm)</td><td>2</td><td>100</td><td>80.6/64</td><td>1.8</td><td>40</td></tr>
<tr><td>Allowable Pressure Drop(bar)</td><td>Coated/ Uncoated</td><td>Flow Reynolds Number</td><td>Specific Gravity</td><td>Buried/Surface</td><td>Compressibility Factor</td><td></td></tr>
<tr><td>16.6</td><td>coated</td><td>4000</td><td>1.326</td><td>Buried</td><td>1.383</td><td></td></tr>
<tr><td colspan="7">Nigeria Gas Company (NGC) Western Division
Physical Configuration: From Okitipupa Ondo to Shagamu Lagos
Terrain transversed: From Okitipupa Ondo to Shagamu Lagos
Design Standard Code: ANSI/ASME B31.8 Standard Code</td></tr>
<tr><td>Length(km)</td><td>Diameter(cm)</td><td>Manifolds</td><td>Design Pressure(bar)</td><td>Input/Output Pressure(bar)</td><td>Flow Rate(m^3/s</td><td>Operating Temperature (^{0}C)</td></tr>
<tr><td>153</td><td>36"(91.44cm)</td><td>2</td><td>100</td><td>64/44.4</td><td>1.8</td><td>40</td></tr>
<tr><td>Allowable Pressure Drop(bar)</td><td>Coated/ Uncoated</td><td>Flow Reynolds Number</td><td>Specific Gravity</td><td>Buried/Surface</td><td>Compressibility Factor</td><td></td></tr>
<tr><td>19.6</td><td>coated</td><td>4000</td><td>1.326</td><td>Buried</td><td>1.383</td><td></td></tr>
</table>

(Source :ElfTotal Nig. Ltd, Shell Petroleum Development Company, Agip Nig. Ltd, Nigeria Gas Company (Eastern Division), Nigeria Gas Company (Western Division))

Table 2: Gas Composition for The Case Study Pipelines

C_1	C_2	C_3	IC_4	NC_4	IC_5	NC_5	C_6	C_7	N_2	CO_2
ElfTotalNig. Ltd										
0.84505	0.0427	0.025	0.010	0.009	0.007	0.006	0.0015	0.00	0.00	0.047
Shell Petroleum Development Company										
0.88800	0.05423	0.2882	0.0072	0.009	0.0038	0.00	0.0018	0.00166	0.0002	0.0076
Agip Nig. Ltd										
0.8436	0.04116	0.2315	0.0165	0.0111	0.004	0.0033	0.0045	0.0033	0.00645	0.05
Nigeria Gas Company (Eastern Division)										
0.85	0.03795	0.02915	0.0155	0.0101	0.004	0.0033	0.00045	0.0003	0.00645	0.05
Nigeria Gas Company (Western Division)										
0.85	0.03795	0.02915	0.0155	0.0101	0.004	0.0033	0.00045	0.0003	0.00645	0.05

(Source :ElfTotal Nig. Ltd, Shell Petroleum Development Company, Agip Nig. Ltd, Nigeria Gas Company (Eastern Division), Nigeria Gas Company (Western Division))

Computer Simulation of The Optimization Models

```
% Computer Programmed for The Determination of The
  Optimal Flow Parameters (SHELL PAN A)
% Initialization
% Upstream Pressure at OBITE, P1(bar))
   P1=84.1;
% Downstream presssure at BONNY, P2(bar)
   P2=71.0;
% Base pressure, Pbj
Pb=1.03;
% Base temperature, Tb
  Tb=291;
% To calculate average flow pressure, P3
   P3=(2/3)*(P1^3-P2^3)/(P1^2-P2^2);
disp('P3')
fprintf('%7.3f\n',P3)
%  Average flow temperature
    T=313;
% Line diameter(cm), D
   D=92.44;
% Elevation above datum, h
   h=5500;
%  Acceleration due gravity, g
   g=9.8;
%  Gsa density
   GD=73.2404/10^4;
% Pump isentropin efficiency, ni
ni=0.85;
% Universal gas constant, R0
   R0=8314/10^5;
% Weymouth constant
%  KW=78.85;
% Panhandle A constsnt
```

```
  KPA=1.90826;
% Modified Panhandle B constant
%   KPB=45.03;
% Weymouth exponent, nw
%  nw=0.5;
% Panhandle A exponent, np
  n=0.5394;
% Modified Panhandle B exponent, nb
%   nb=0.51;
% Pipe inlet and exit conditions
% Well rounded inlet coeffient, k4
 K41=0.04;
% Well rounded exit coefficient, k5
 K51=1.0;
% Pump isentropic efficiency, n1
 n1=0.95;
% Kinetic energy flux coeffiicient, A2
 A2=1.036;
% Area ratio, AR
 AR=1.0;
% Equivalent length of one globe valves, LEV(m)
  LEV=350*D;
% Equivalent length of 13 globe valves
LEVn=(13*LEV)/1000;
% Equivalent length of one Tee-joint
% Flow through run
  LET1=20*D;
% Flow through branch
  LET2=60*D;
% Total effective length for 13 Tee-joint
LETn=(13*(LET1+LET2))/1000;
% Line lehgth(Km), LL
 L=131+(LEVn+LETn);
for Q=86400:43200:518400
disp('When Q is')
fprintf('%6.2f\n',Q)
% Mean flow velocity, Vm/s)
 V=(4*Q)/(pi*D^2);
% Pressure ratio, CP
  CP=2*(P2-P1)/(GD*V^2);
%  Average composition of the gas from production line for the month of August 2008(mole fraction)
C1A=0.869859;C2A=0.054574;C3A=0.020709;IC4A=0.004517;NC4A=0.006309;IC5A=0.002178;NC5A=0.0
01787;C6A=0.004627;N2A=0.000598;CO2A=0.034843;
%  Gas density
%   GD=73.2924
%   Average composition of the gas from production line for the
%   month of January 2006(mole fraction)
C1J=0.707881;C2J=0.052663;C3J=0.026519;IC4J=0.005379;NC4J=0.007883;IC5J=0.002642;NC5J=0.002116
;C6J=0.004207;N2J=0.001332;CO2J=0.028088;
%  Gas density
  GD=77.8621
%   Molar mass of gaseous components
M11=16;M21=30;M31=44;M4I1=54;M4N1=54;M5I1=72;M5N1=72;M61=86;M71=100;M81=114;M91=128;
M101=142;MN21=28;MCO21=44;
  MAIR=28.97;
%  Average molecular mass of gaseous mixture(PRODUCTION) in January, 2006
%
MGASJ=(C1J*M11+C2J*M21+C3J*M31+IC4J*M4I1+NC4J*M4N1+IC5J*M5I1+NC5J*M5N1+C6J*M61+
N2J*MN21+CO2J*MCO21);
```

```
% Specific gravity of the mixture for the month of January, 2006
% GAJ=MGASJ/MAIR;
% Average molecular mass of gaseous mixture(PRODUCTION) in August, 2008
MGASA=(C1A*M11+C2A*M21+C3A*M31+IC4A*M4I1+NC4A*M4N1+IC5A*M5I1+NC5A*M5N1+C6A*
M61+N2A*MN21+CO2A*MCO21);
% Specific gravity of the mixture for the month of August, 2008
    GAA=MGASA/MAIR;
% Gas density, GD
%     GD=(P3*MGASA)/(R0*T);
% Gas compressibility factor, Z
  Z=((P3*MGASA)/(GD*8314*T))*10;
disp(' MGASA     GAA      Z')
fprintf('%12.6f\n',MGASA,GAA,Z)
% To calculate gas absolute viscosity, GV(Pas--Ns/m2)
% Absolute viscosity of the hydrocarbon components, GVHC, is expressed as:
 GVHC=(8.188E-3-6.15E-3*(GAA)+(1.709E-5-2.062E-6*log10(GAA))*(1.8*T+0.27))*1.02247E-
5*1.15741E-10;
%  *1.15741E-10;
% Absolute viscosity of Nitrogen component
  GVN=(9.59E-3+8.48E-3*log10(GAA))*N2A*1.02247E-5*1.15741E-10;
% Absolute viscosity of carbon dioxide component
 GVC=(6.24E-3+9.08E-3*log10(GAA))*CO2A*1.02247E-5*1.15741E-10;
 GV=GVHC+GVN+GVC;
disp('GV'  )
fprintf('%30.25f\n',GV)
% At the optimal value of Q, dF/dQ=0
% Pump constant, kpp
kpp=(16*GD*(1-n1)/(pi^2*D^4));
% Determination of the optimal flow capacity
K1PA=1.5^(0.0788)*KPA*(1/10^5)^(0.5394)*(Tb/Pb)^(1.0728)*(MAIR/MGASA)^(0.4606)*((GD*(1/10^4)*
R0*T*(P1+P2))/(MGASA*(P1^2+P2^2+P1*P2)))^0.0788*((P1+P2)/(T*L))^0.5394*D^2.6182;
K11=((0.0112*GD*L)/(pi^2*D^5))+((8*GD)/(pi^2*D^4))+((8*GD*(K41+A2-
1))/(pi^2*D^4))+((8*K51*GD)/(pi^2*D^4));
 K12=(1-
1/AR^2)*((8*GD)/(pi^2*D^4))+((0.0112*GD*LEVn)/(pi^2*D^5))+((0.0112*GD*LETn)/(pi^2*D^5))+((16*G
D*(1-ni))/(pi^2*D^4));
 K1=(K11+K12);
 K2=0.0014*K1PA^(-1.8539);
K3=((1/(pi^2*D^5))*(0.9256*(GD)^0.68*L*(D*GV)^0.32+0.9256*(GD)^0.68*LEVn*(D*GV)^0.32+0.9256*(
GD)^0.68*LETn*(D*GV)^0.32));
%K4=(0.1157*K1PA^(-1.8539)*((D*GV)/(GD*(1/10^4))^0.32);
 K4=(0.1157*K1PA^(-1.8539)*((D*GV)/(GD^0.32)));
disp('K1PA,  K1.  K2,  K3,   K4')
fprintf('%20.15f\n',K1PA,K1,K2,K3,K4)
%DF1=((K1PA*GD^0.32*n))*((K1*Q^0.4661+K2*Q^0.32+K3*Q^0.1461+K4+(GD*g*h*Q^(-
1.5339)/1000)/(0.0014*(GD*Q)^0.32+0.1157*(D*GV)^0.32))^(n-1));
DF1=((K1PA*GD^0.32*n))*((K1*Q^0.4661+K2*Q^0.32+K3*Q^0.1461+K4+GD*(1/10^3)*g*h*Q^(-
1.5339))/(0.0014*(GD*Q)^0.32+0.1157*(D*GV)^0.32))^(n-1);
DF2=(0.0014*(GD*Q)^0.32+0.1157*(D*GV)^0.32);
DF3=(K1*Q^0.4661+K2*Q^0.32+K3*Q^0.1461+K4+GD*(1/10^3)*g*h*Q^(-1.5339))*(4.48*10^(-
4)*(GD)^0.32*Q^(-0.68));
DF4=0.4661*K1*Q^(-0.5339)+0.32*K2*Q^(-0.68)+0.1461*K3*Q^(-0.8539)-1.5339*GD*(1/10^3)*g*h*Q^(-
2.5339);
DF5=(0.0014*(GD*Q)^(0.32)+0.1157*(D*GV)^(0.32))^(2);
disp('DF1,DF2,DF3,DF4,DPF5')
fprintf('%20.15f\n',DF1,DF2,DF3,DF4,DF5)
 DF=(DF1*((DF2*DF4)+DF3)/DF5);
DPov=(K1*Q^2+K2*Q^1.8539+K3*Q^1.68+K4*Q^1.5339)+((GD*g*h)/(10^3));
  DPov1=(K1*Q^2);
```

```
   DPov2=K2*Q^1.8539;
   DPov3=K3*Q^1.68;
   DPov4=K4*Q^1.5339;
   DPov5=GD*g*h/(10^3);
disp('DPov1,DPov2,DPov3,DPov4,DPov5')  fprintf('%20.15f\n',DPov1,DPov2,DPov3,DPov4,DPov5)
disp('DPov')
fprintf('%20.10f\n',DPov)
% At the optimal flow capacity, DF=0
if DF<=0
disp(' DF        Q       DPov')
fprintf('%20.10f\n',DF,Q,DPov)
else
disp('conditions not met')
disp(' DF        Q       DPov')
fprintf('%20.10f\n',DF,Q,DPov)
end
end

% Computer Programme For The Determination of The Optimal
% Maximum orMinimum Values of Flow Capacity and Pressure
%  Drop((PANHANDLE   A)
      Q=Oop;
      DF1=K1PA*GD^(0.32)*n*(n-1);
DF2=K1*Q^(0.4661)+K2*Q^(0.32)+K2*Q^(0.1461)+K4+GD*g**h*Q^(-1.5339);
DF3=0.0014*(GD*Q)^(0.32)+0.1157*(D*GV)^(0.32);
      DF4=2.0454E-04*GD^(0.32)*K1*Q^(-0.2139);
      DF5=(0.0539*(D*GV)^(0.32)-2.4346E-4*GD*(0.32)*K3)*Q^(-0.5339);
      DF6=(0.037*(D*GV)^(0.32)*K2-4.48E-4*GD^(0.32))*Q^(-0.68);
      DF7=0.0169*(D*GV)^(0.32)*K2*Q*(-0.8539);
      DF8=0.1775*(D*GV)^(0.32)*GD*g*h*Q^(-2.5339);
      DF9=-2.5955e-3*GD^(0.32)*GD*g*h*Q^(-2.5339);
      DF10=DF3^(2);
DF11=K1PA*GD^(0.32)*n;
DF12=DF2/df3;
DF13=DF10;
DF14=-4.3751e-5*GD^(0.32)**K1*Q*(-1.2139);
DF15=-(1.4E-4*K3+0.02878*(D*GV)^(0.32))*Q^(-1.5339);
DF16=-(0.03516*(D*GV)^(0.32)-3.0464E-4*GD^(0.32)*Q^(-1.68);
DF17=-0.0144*(D*GV)^(0.32)*K2*Q^(-1.8539);
DF18=0.005746*GD^(0.32)*GD*g*h*Q^(-3.2139);
DF19=0.4498*(D*GV)^(0.32)*GD*g*h*Q^(-3.5339);
DF20=-8.96E-4*GD^(0.32)* (0.0014*(GD*Q)^(0.32)+0.1157*(D*GV)*(0.32)*Q^(-0.68);
DF21=8.96E-4*GD^(0.32)*(0.0014*(GD*Q)^(0.32)+0.1157*(D*GV)^(0.32)*Q^(-0.68);
DF22=2.0454E-4*GD^(0.32)*K1*Q^(-0.2139);
DF23=(0.0539*(D*GV)*(0.32)-2.4346E-4^GD^(0.32)*K3)*Q^(-0.5339);
DF24=0.037*(D*GV)^(0.32)-4.48E-4*GD^(0.32))*Q^(-0.68);
DF25=0.0169*(D*GV)^(0.32)*K2*Q^(-0.8539);
DF26=0.1775*(D*GV)^(0.32)*GD*g*h*Q^(-2.5339);
DF27=-2.5955E-3*GD^(0.32)*GD*g*h*Q^(-2.5339);
DF28=DF3^4;
FDD=DF1*(DF2/DF3)^(n-2)*((DF4+DF5+DF6+DF7+DF8+DF9)/DF10)^(2)+DF11*DF12^(n-1)*
((DF13*(DF14+DF15+DF16+DF17+DF18+DF19+DF20)-
DF21*(DF22+DF23+DF24+DF25+DF26+DF2&)/DF28);
if FDD>0
disp('The optimal Minimum value of Q is')
fprintf('%20.10f\',Q)
else
disp('The optimal Maximum value of Qis')
fprintf('%20.10f\',Q)
```

end

Computer Program for Graphical Presentation of Results

```
% ELF Panhandle B for 36"(0.9144m)
DQop=[-25.413,-24.2427,-8.868,6.608,20.301,41.18,52.9,64.413,77.868,86.991,104.559,118.285];
DD=[-15,-10,-5,5,10,20,25,30,35,40,45,50];
DP1=[-30,-20,-10,10,20,40,50,60,70,80,90,100];
DP2=[-30,-20,-10,10,20,40,50,60,70,80,90,100];
DL=[-15,-10,-5,5,10,20,25,30,35,40,45,50];
%PD=[15.48,12.91,12.34,11.06,10.33,6.56];
plot(DD,DQop,DP1,DQop,DP2,DQop,DL,DQop)
%xlabel('P1/P1')
ylabel('Qopt/Qopt')
title('Graph of Change in Optimal Flow Capacity to Optimal flow Capacity and Change in Upstream Pressure to Upstream Pressure ')
%gtext('Upstream/Optimal Line Pressure Drop'),gtext('Downstrean/Optimal Line Pressure Drop
```

II. RESULTS AND DISCUSSION

The results of optimization of flow variables are in the tables below :

Table 3 : Results of Optimal Flow-- ElfTotal Nig. Ltd

	MODEL FLOW EQUATIONS		OPTIMIZATION MODELS	
	OPEATING CONDITIONS	PAN A	OPEATING CONDITIONS	PAN A
FLOW CAPACITY	1.8m³/s	1.5m³/s	1.8m³/s	1.915m ³/s
PRESSURE DROP	20bar	21.1bar	20bar	15.91bar
AMBIENT TETEMPERATURE	291K		291K	
BULK TEMPERATURE	313K		313K	

Table 4 : Results of Optimal Flow--Shell Company (SPDC)

	MODEL FLOW EQUATIONS		OPTIMIZATION MODELS	
	OPEATING CONDITIONS	PAN A	OPEATING CONDITIONS	PAN A
FLOW CAPACITY	1.8m³/s	1.5m³/s	1.8m³/s	1.9422m³/s
PRESSURE DROP	19.6bar	18bar	19.6bar	17.7535bar
AMBIENT TETEMPERATURE	291K		291K	
BULK TEMPERATURE	313K		313K	

Table 5 : Results of Optimal Flow--Agip Nig. Ltd

	MODEL FLOW EQUATIONS		OPTIMIZATION MODELS	
	OPEATING CONDITIONS	PAN A	OPEATING CONDITIONS	PAN A
FLOW CAPACITY	$1.8m^3/s$	$1.5m^3/s$	$1.8m^3/s$	$1.94m^3/s$
PRESSURE DROP	21.1bar	21.1bar	21.1bar	28.74bar
AMBIENT TETEMPERATURE	291K		291K	
BULK TEMPERATURE	313K		313K	

Table 6 : Results of Optimal Flow--Nigeria Gas Company (NGC)

Eastern Division

	MODEL FLOW EQUATIONS		OPTIMIZATION MODELS	
	OPEATING CONDITIONS	PAN A	OPEATING CONDITIONS	PAN A
FLOW CAPACITY	$1.8m^3/s$	$1.59m^3/s$	$1.8m^3/s$	$1.938m^3/s$
PRESSURE DROP	16.6bar	16.6bar	16.6bar	12.5bar
AMBIENT TETEMPERATURE	291K		291K	
BULK TEMPERATURE	313K		313K	

Table 7 : Results of Optimal Flow--Nigeria Gas Company (NGC)

Western Division

	MODEL FLOW EQUATIONS		OPTIMIZATION MODELS	
	OPEATING CONDITIONS	PAN A	OPEATING CONDITIONS	PAN A
FLOW CAPACITY	$1.8m^3/s$	$1.59m^3/s$	$1.8m^3/s$	$1.938m^3/s$
PRESSURE DROP	19.6bar	19.6bar	19.6bar	10.91bar
AMBIENT TETEMPERATURE	291K		291K	
BULK TEMPERATURE	313K		313K	

Tables 3 to 7 show the conditions of the pipelines subject to the operational and optimized conditions. The percentage reduction in pressure drop viz-a-viz the percentage increase in flow throughput under the optimized conditions for all the case study pipelines are as shown in Table 8.

Case Study Gas Pipelines	% Reduction in Line Pressure Drop (bar)	% Increase in Flow Throughput (m^3/s)
ElfTotal Nig. Ltd	20.45	6.4
Shell Company (SPDC)	9.42	7.9

Agip Nig. Ltd	**-3.6**	**7.78**
Nigeria Gas Company (Eastern Division)	**24.7**	**7.7**
Nigeria Gas Company (Western Division)	**44.34**	**7.7**

Table 8 : Reduction in Line Pressure Drop-Increase in Flow Throughput Under Optimized ConditionApparently, there could be a significant improvement on the line pressure drop to the tune of 10 to 45%. Additional flow throughput of 8% above the normal operational level could also be accommodated.

III. RECOMMENDATION AND CONCLUSION

(i) The optimization scheme clearly confirmed that the present operating conditions of our gas pipelines are truly not optimal. There is therefore urgent need to generate new Design equations incorporating the optimal models for the production of efficient pipelines for future applications. This is to ensure that the operating pipelines and new pipelines networks for gas transmission are not under operated in terms of Pressure-Flow capacity requirements. The design review and analysis would clearlyreduce the cost of design, construction and operations of gas pipelines, associated equipment and facilities. Thus, to plan, set up, operate and execute a gas pipeline at effective cost could be realizable if the optimal pressure-flow capacity requirements are ascertained at the Design and material specification stages.
(ii)In-depth research work is recommended in the area of theoretical, practical and economic consideration of flow compressibility effects as well as hydration problems in sub-cooled under water offshore pipelines. Adequate knowledge of compressibility effects on pressure drop and pressure gradient will go a long way in ascertaining the operating pressure-temperature characteristics of pipelines so as to correlate the operating measured conditions.
(iii) Critical review of as-installed physical, geometric and flow features of gas pipelines for more exact evaluation of losses in fluid energy. If the factors influencing the loss of fluid energy are thoroughly evaluated, the required overall pressure drop in a gas pipeline could be closely specified. This will off-set the problem of underrating or overrating the Pressure–Flow capacity requirements for gas pipelines. This would also aid the sizing of compressors, pumps, valves, fittings and metering devices.
(iv) This optimization and sensitivity analysis is limited to single phase flow of gas. Future research is envisaged to also address optimization models for two phase flow of gas in gas transmission pipelines[PhD Yhesis].

Conclusion

Gas Pipeline flow optimization models developed by the researcher for single phase flow of gas have simulated by computationapproach. The simulation results clearly confirmed that there could drastic reduction in pressure drop for the optimized gas pipelines. Additional throughput of about 10% could be accommodated over the normal operational level. Analysis of the optimization results clearly confirmed that operating optimally would have significant impact in reducing the cost of investment and operation of as installed gas pipelines, even the future generation of gas pipelines to be in Nigerian terrain.

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