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Flow Optimization Sensitivity in Natural Gas Pipeline Network System

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Abstract:
Three control variables of interest namely upstream pressure, downstream pressure and gas specific gravity were considered to determine the sensitivities of the optimal flow capacity to changes in the aforementioned control variables. The sensitivity scheme covered five case study Pipelines namely: Elf Total Nig. Ltd, Shell Petroleum Development Company (SPDC), Agip Nig. Ltd and Nigeria Gas Company (NGC) Eastern Division. The Panhandle A and Modified Panhandle B models equations were both applied to each of the pipelines in the sensitivity evaluation scheme.
The sensitivities were calculated with respect to small changes in upstream pressure P_1, downstream pressure P_2 and the gas specific gravity G, within the limit of ±20 %.
It was seen that changes in optimal flow capacities were insignificant and therefore insensitive to changes in flow variables in the range upto±20 %. This gives credence, authenticates and establish the stability of the results of optimization of flow capacities carried out in the researcher's previous works. The Panhandle-A flow model yielded lower values of changes in optimal flow capacities upto the limit of 1.0 %. In comparison, the Panhandle-B flow model gave sensitivities upto a maximum of 9.0 %, for all the Pipelines covered in the study and the flow control variables.
In more explicit manner, the response of optimal flows capacities to changes in control variables for the transformed Panhandle-A and Modified Panhandle-B models for ElfTotal Nig. Ltd with respect to upstream pressure, downstream and gas specific gravity are respectively 0.4 %, 0.9 % and 0.16 % (Tables 1 a to 1b). Applying the same concept to Shell petroleum Development Company (SPDC), the response are respectively 3.2 %, 1.7 % and 0.16 % (Tables 2a to 2b). In the same vein, with respect to Agip Nig. Ltd, the respective data are 7.11 %, 0.03 % and 3.7 % (Tables 3a to 3b) and for the Nigeria Gas Company (NGC) Eastern Division the respective data are 7.11 %, 0.03 % and 3.7 % (Tables 4a and 4b). The graphical illustrations are in accordance with Figures (Fig.1a & b to 4a & b).
The operating threshold based on off design analysis (Tables 6 to 10) confirmed that the line flow throughput could be varied within 1 m^3/s to 6.5 m^3/s. The nominal line diameter could be fixed within 30" and 65". These condition are possible within the limit of pressure variation in the range of 30 bar to 170 bar at stream temperature of 40 ^0C.

Keywords: *Control variables, upstream pressure, downstream pressure, specific gravity, sensitivities, sensitivity evaluation, stability*

1. 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 [1, 2, 3]. Flow optimization sensitivity evaluation scheme could enable these assets to be put to optimal use throughout their design life. Nigeria as a nation is blessed with abundant reserve of Natural gas, conservatively put at approximately 185 trillion standard cubic feet [4].

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. It is the view of the researcher that sensitivity evaluation of optimal flows would build the reliability and stability level of the results of optimal flow variables. The results of the sensitivity scheme coupled with the optimal values of flow variables would build the confidence to applying the optimal results in the design, construction and operation of our future generation gas pipeline network system.

Relevant Mathematical Model

(i) Panhandle-A Optimization Models

The optimization function equation is expressed as [5, 6]:

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

Differentiating equation 1 with respect to Q,

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

$$\frac{\left\{\begin{array}{l}\left(0.0014(\rho Q)^{0,32}+0.1157\left(D\mu_G\right)^{0.32}\right)\left(\begin{array}{l}0.4661K_1Q^{-0.5339}+0.32K_2Q^{-0.68}+0.1461K_3Q^{-0,8539}+\\-1.5339\rho g\Delta HQ^{-2.5339}\end{array}\right)\\-\left(\left(K_1Q^{0.4661}+K_2Q^{0.32}+K_3Q^{0.1461}+K_4+\rho g\Delta HQ^{-1.5339}\right)\right)\left(4.48\times10^{-4}\rho^{0.32}Q-0.68\right)\end{array}\right\}}{\left(0.0014(\rho Q)^{0,32}+0.1157\left(D\mu_G\right)^{0.32}\right)^2}$$

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

$$\frac{\left\{\begin{array}{l}2.0454\times10^{-4}\rho^{0.32}K_1Q^{-0.2139}+\left(0.0539\left(D\mu_G\right)^{0.32}-2.4346\times10^{-4}\rho^{0.32}K_3\right)Q^{-0.5339}\\+\left(0.037\left(D\mu_G\right)^{0.32}K_2-4.48\times10^{-4}\rho^{0.32}\right)Q^{-0.68}+0.0169\left(D\mu_G\right)^{0.32}K_2Q^{-0.8539}\\+0.1775\left(D\mu_G\right)^{0.32}\rho g\Delta HQ^{-2.5339}-2.5955\times10^{-3}\rho^{0.32}\rho g\Delta HQ^{-2.5339}\end{array}\right\}}{\left(0.0014(\rho Q)^{0,32}+0.1157\left(D\mu_G\right)^{0.32}\right)^2} \qquad (2)$$

Differentiating Equation (2) twice with respect to Q

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

$$\left\{\frac{\begin{array}{l} 2.0454\times10^{-4}\rho^{0.32}K_1 Q^{-0.2139} + \left(0.0539\left(D\mu_G\right)^{0.32} - 2.4346\times10^{-4}\rho^{0.32}K_3\right)Q^{-0.5339} \\ + \left(0.037\left(D\mu_G\right)^{0.32}K_2 - 4.48\times10^{-4}\rho^{0.32}\right)Q^{-0.68} + 0.0169\left(D\mu_G\right)^{0.32}K_2 Q^{-0.8539} \\ + 0.1775\left(D\mu_G\right)^{0.32}\rho g\Delta H Q^{-2.5339} - 2.5955\times10^{-3}\rho^{0.32}\rho g\Delta H Q^{-2.5339} \end{array}}{\left(0.0014(\rho Q)^{0,32} + 0.1157\left(D\mu_G\right)^{0.32}\right)^2}\right\}^2$$

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

$$\frac{\left\{\begin{array}{l} \left\{\left(0.0014(\rho Q)^{0,32} + 0.1157\left(D\mu_G\right)^{0.32}\right)^2\right\}\left[\begin{array}{l} -4.3751\times10^{-5}\rho^{0.32}K_1 Q^{-1.2139} \\ -\left(1.3\times10^{-4}\rho^{0.32}K_3 + 0.02878\left(D\mu_G\right)^{0.32}\right)Q^{-1.5339} \\ -\left(0.02516\left(D\mu_G\right)^{0.32} - 3..0464\times10^{-4}\rho^{0.32}\right)Q^{-1.68} \\ -0.0144\left(D\mu_G\right)^{0.32}K_2 Q^{-1.8539} \\ +0.005746\rho^{0.32}\rho g\Delta H Q^{-3.2139} \\ -0.4498\left(D\mu_G\right)^{0.32}\rho g\Delta H Q^{-3.5339} \end{array}\right] - \\ 8.96\times10^{-4}\rho^{0.32}\left(0.0014(\rho Q)^{0,32} + 0.1157\left(D\mu_G\right)^{0.32}\right)Q^{-0.68}\left\{\begin{array}{l} 2.0454\times10^{-4}\rho^{0.32}K_1 Q^{-0.2139} \\ +\left(0.0539\left(D\mu_G\right)^{0.32} - 2.4346\times10^{-4}\rho^{0.32}K_3\right)Q^{-0.5339} \\ +\left(0.037\left(D\mu_G\right)^{0.32}K_2 - 4.48\times10^{-4}\rho^{0.32}\right)Q^{-0.68} \\ +0.0169\left(D\mu_G\right)^{0.32}K_2 Q^{-0.8539} \\ +0.1775\left(D\mu_G\right)^{0.32}\rho g\Delta H Q^{-2.5339} \\ -2.5955\times10^{-3}\rho^{0.32}\rho g\Delta H Q^{-2.5339} \end{array}\right\} \end{array}\right\}}{\left(0.0014(\rho Q)^{0,32} + 0.1157\left(D\mu_G\right)^{0.32}\right)^4} \quad (3)$$

(ii) Modified Panhandle-B Optimization Models

The optimization function equation is expressed as:

$$F(Q)=K_{1PB}\left[\frac{\rho^{0.32}\left(K_1Q^{0.3592}+K_2Q^{0.32}+K_3Q^{0.0392}+K_4+\rho g\Delta HQ^{-1.6408}\right)}{0.0014(\rho Q)^{0,32}+0.1157(D\mu_G)^{0.32}}\right]^{n}-1 \qquad (4)$$

Differentiating Equation (4) with respect to Q

$$\frac{\partial F(Q)}{\partial Q}=K_{1PB}\rho^{0.32}n\left[\frac{\rho^{0.32}\left(K_1Q^{0.3592}+K_2Q^{0.32}+K_3Q^{0.0392}+K_4+\rho g\Delta HQ^{-1.6408}\right)}{0.0014(\rho Q)^{0,32}+0.1157(D\mu_G)^{0.32}}\right]^{n-1}\times$$

$$\frac{\left\{\begin{array}{l}\left(0.0014(\rho Q)^{0.32}+0.1157\left(D\mu_G\right)^{0.32}\right)\left(\rho^{0.32}\left(\begin{array}{l}0.3592K_1Q^{-0.6408}+0.32K_2Q^{-0.68}+0.0392K_3Q^{-0.9608}\\-1.6408\rho g\Delta HQ^{-2.6408}\end{array}\right)\right)\\-\left(K_1Q^{0.3592}+K_2Q^{0.32}+K_3Q^{0.0392}+K_4+\rho g\Delta HQ^{-1.6408}\right)\left(4.48\times10^{-4}\rho^{0.32}Q^{-0.68}\right)\end{array}\right\}}{\left(0.0014(\rho Q)^{0,32}+0.1157\left(D\mu_G\right)^{0.32}\right)^2}$$

$$=K_{1PB}\rho^{0.32}n\left[\frac{\rho^{0.32}\left(K_1Q^{0.3592}+K_2Q^{0.32}+K_3Q^{0.0392}+K_4+\rho g\Delta HQ^{-1.6408}\right)}{0.0014(\rho Q)^{0,32}+0.1157(D\mu_G)^{0.32}}\right]^{n-1}\times$$

$$\frac{\left\{\begin{array}{l}K_1\left(0.1149\rho^{0.64}-4.48\times10^{-4}\rho^{0.32}\right)Q^{-0.3208}+4.48\times10^{-4}K_2\left(\rho^{0.64}-\rho^{0.32}\right)Q^{-0.36}\\\left(5.488\times10^{-5}\rho^{0.64}K_3+0.0416\rho^{0.32}\left(D\mu_G\right)^{0.32}K_1-4.48\times10^{-4}\rho^{0.32}K_3\right)Q^{-0.6408}\\-2.7451\times10^{-3}\rho^{0.32}\rho g\Delta HQ^{-2.3208}+\left(0.037\rho^{0.32}\left(D\mu_G\right)^{0.32}K_2-4.48\times10^{-4}\rho^{0.32}K_4\right)Q^{-0.68}\\+4.5394\times10^{-3}K_3\left(D\mu_G\right)^{0.32}Q^{-0.9608}-0.1898\rho^{0.32}\left(D\mu_G\right)^{0.32}\rho g\Delta HQ^{-2.6408}\end{array}\right\}}{\left(0.0014(\rho Q)^{0,32}+0.1157\left(D\mu_G\right)^{0.32}\right)^2} \qquad (5)$$

Differentiating Equation (5) with respect to Q

$$\frac{\partial F^2(Q)}{\partial Q^2}=A\times B+\frac{C(D-E)}{F} \qquad (6)$$

Where:

$$A=K_{1PB}\rho^{0.32}n(n-1)\left[\frac{\rho^{0.32}\left(K_1Q^{0.3592}+K_2Q^{0.32}+K_3Q^{0.0392}+K_4+\rho g\Delta HQ^{-1.6408}\right)}{0.0014(\rho Q)^{0,32}+0.1157(D\mu_G)^{0.32}}\right]^{n-2}$$

$$B = \left\{ \frac{\left\{ \begin{array}{l} K_1\left(0.1149\rho^{0.64} - 4.48\times10^{-4}\rho^{0.32}\right)Q^{-0.3208} + 4.48\times10^{-4}K_2\left(\rho^{0.64} - \rho^{0.32}\right)Q^{-0.36} \\ \left(5.488\times10^{-5}\rho^{0.64}K_3 + 0.0416\rho^{0.32}\left(D\mu_G\right)^{0.32}K_1 - 4.48\times10^{-4}\rho^{0.32}K_3\right)Q^{-0.6408} \\ -2.7451\times10^{-3}\rho^{0.32}\rho g\Delta HQ^{-2.3208} + \left(0.037\rho^{0.32}\left(D\mu_G\right)^{0.32}K_2 - 4.48\times10^{-4}\rho^{0.32}K_4\right)Q^{-0.68} \\ 4.5394\times10^{-3}K_3\left(D\mu_G\right)^{0.32}Q^{-0.9608} - 0.1898\rho^{0.32}\left(D\mu_G\right)^{0.32}\rho g\Delta HQ^{-2.6408} \end{array} \right\}^2}{\left(0.0014(\rho Q)^{0,32} + 0.1157\left(D\mu_G\right)^{0.32}\right)^2} \right\}$$

$$C = K_{1PA}\rho^{0.32}n\left[\frac{\rho^{0.32}\left(K_1Q^{0.3592} + K_2Q^{0.32} + K_3Q^{0.0392} + K_4 + \rho g\Delta HQ^{-1.6408}\right)}{0.0014(\rho Q)^{0,32} + 0.1157\left(D\mu_G\right)^{0.32}}\right]^{n-1}$$

$$D = \left\{\left(0.0014(\rho Q)^{0,32} + 0.1157\left(D\mu_G\right)^{0.32}\right)^2\right\}\left[\begin{array}{l} K_1\left(1.4372\times10^{-4}\rho^{0.32} - 0.0369\rho^{0.64}\right)Q^{-1.3208} - 1.6128\times10^{-4}K_2\left(\rho^{0.64} - \rho^{0.32}\right)Q^{-1.36} \\ \left(2.8708\times10^{-4}\rho^{0.32}K_3 - 0.0267\rho^{0.32}\left(D\mu_G\right)^{0.32}K_1 - 3.5167\times10^{-5}\rho^{0.64}K_3\right)Q^{-1.6408} \\ +6.3708\times10^{-3}\rho^{0.32}\rho g\Delta HQ^{-3.3208} + \left(3.0464\times10^{-4}\rho^{0.32}K_4 - 0.0252\rho^{0.32}\left(D\mu_G\right)^{0.32}K_2\right)Q^{-1.68} \\ -4.3615\times10^{-3}\left(D\mu_G\right)^{0.32}K_3Q^{-1.9608} + 0.5012\rho^{0.32}\left(D\mu_G\right)^{0.32}\rho g\Delta HQ^{-3.6408} \end{array}\right]$$

$$E = 8.96\times10^{-4}\rho^{0.32}\left(0.0014(\rho Q)^{0,32} + 0.1157\left(D\mu_G\right)^{0.32}\right)Q^{-0.68}\left\{\begin{array}{l} K_1\left(0.1149\rho^{0.64} - 4.48\times10^{-4}\rho^{0.32}\right)Q^{-0.3208} \\ +4.48\times10^{-4}K_2\left(\rho^{0.64} - \rho^{0.32}\right)Q^{-0.36} \\ \left(\begin{array}{l} 5.488\times10^{-5}\rho^{0.64}K_3 + 0.0416\rho^{0.32}\left(D\mu_G\right)^{0.32}K_1 \\ -4.48\times10^{-4}\rho^{0.32}K_3 \end{array}\right)Q^{-0.6408} \\ -2.7451\times10^{-3}\rho^{0.32}\rho g\Delta HQ^{-2.3208} \\ +\left(0.037\rho^{0.32}\left(D\mu_G\right)^{0.32}K_2 - 4.48\times10^{-4}\rho^{0.32}K_4\right)Q^{-0.68} \\ 4.5394\times10^{-3}K_3\left(D\mu_G\right)^{0.32}Q^{-0.9608} \\ -0.1898\rho^{0.32}\left(D\mu_G\right)^{0.32}\rho g\Delta HQ^{-2.6408} \end{array}\right\}$$

$$F = \left(0.0014(\rho Q)^{0,32} + 0.1157\left(D\mu_G\right)^{0.32}\right)^4$$

1.1 .Results and Discussions

The optimal flow capacity sensitivities were calculated and presented in Tables 1 to 4. The sensitivities are also graphically illustrated in Figures 1 to 4. These covered the four Pipelines namely: ElfTotal Nig. Ltd, Shell Petroleum Development Company (SPDC), Agip Nig. Ltd and Nigeria Gas Company (NGC) Eastern Division. The sensitivities were calculated with respect to small changes in upstream pressure P_1, downstream pressure P_2 and the gas specific gravity G to the tune of ±20 %.

PIPELINE : ELFTOTAL OPTIMIZED MODEL : PANHANDLE A								
BASE PARAMETERS :	Upstream Pressure, P_1=84.1 bar; Downstream Pressure, P_2=63bar							
		Operational Flow Capacity, Q=1.8m^3/s; Optimal Flow Capacity, Q_{opt}=1.89m^3/s						
		Specific Gravity, G=0.666; Flow Compressibilty Factor, Z=0.749						
		Line length, L=134km; Line Diameter, D=36" (0.9144m)						
$\Delta P_1/P_1$ (%)	-20	-10	0	0.5	10	20		
P_{1new}(bar)	67.33	75.69	84.1	84.52	92.51	104.2		
$I\Delta Q_{opt}/Q_{opt}$ (%)I	0.0159	0.445	0	0.0106	0.0212	0.0016		
$\Delta P_2/P_2$ (%)	-20	-10	0	0.5	10	20		
P_{2new}(bar)	50.4	56.7	63	63.325	69.3	75.6		
$I\Delta Q_{opt}/Q_{opt}$ (%)I	0.212	0.0053	0	0.0106	0.0159	0.0159		
$\Delta G/G$ (%)	-20	-10	0	0.5	10	20		
G_{new}	0.53	0.592	0.666	0.66933	0.733	0.798		
$I\Delta Q_{opt}/Q_{opt}$ (%)I	0.159	0.0106	0	0.0106	0.0053	0.00159		

Table 1a : Results Showing Sensitivities of Optimal Flow Capacities to Variability In Operating Condition: ElfTotal Nig. Ltd—Panhandle-A

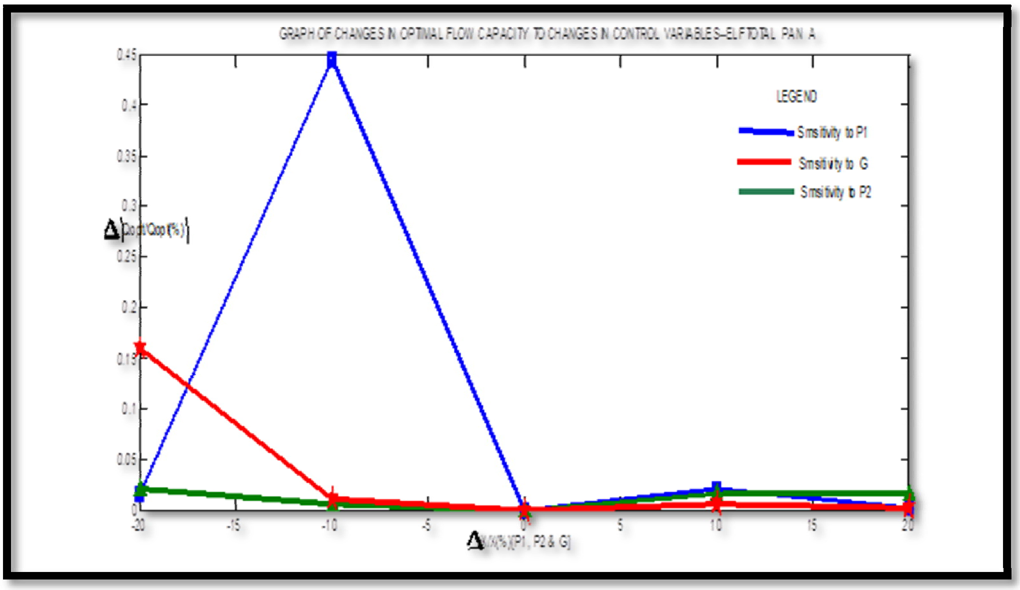

Figure 1a: Graph of Changes in Flow Capacity to Changes in Control Variables: ElfTotal Nig. Ltd --Panhandle-A

PIPELINE : ELFTOTAL OPTIMIZED MODEL : PANHANDLE B								
BASE PARAMETERS :		Upstream Pressure, P_1=84.1 bar; Downstream Pressure, P_2=63bar						
		Operational Flow Capacity, Q=1.8m^3/s; Optimal Flow Capacity, Q_{opt}=2.8197m^3/s						
		Specific Gravity, G=0.666; Flow Compressibilty Factor, Z=0.749						
		Line length, L=134km; Line Diameter, D=36" (0.9144m)						
$\Delta P_1/P_1$ (%)	-20	-10	0	10	20			
P_{1new}(bar)	67.33	75.69	84.1	92.51	104.2			
$I\Delta Q_{opt}/Q_{opt}$ (%)I	0.0142	0.0142	0	0.0426	0.0036			
$\Delta P_2/P_2$ (%)	-20	-10	0	10	20			
P_{2new}(bar)	50.4	56.7	63	69.3	75.6			
$I\Delta Q_{opt}/Q_{opt}$ (%)I	0.0355	0.0355	0	0.0213	0.0071			
$\Delta G/G$ (%)	-20	-10	0	10	20			
G_{new}	0.53	0.592	0.666	0.733	0.798			
$I\Delta Q_{opt}/Q_{opt}$ (%)I	0.1099	0	0	0.0177	0			

Table 1b : Results Showing Sensitivities of Optimal Flow Capacities to Variability In Operating Condition: ElfTotal Nig. Ltd—Panhandle-B

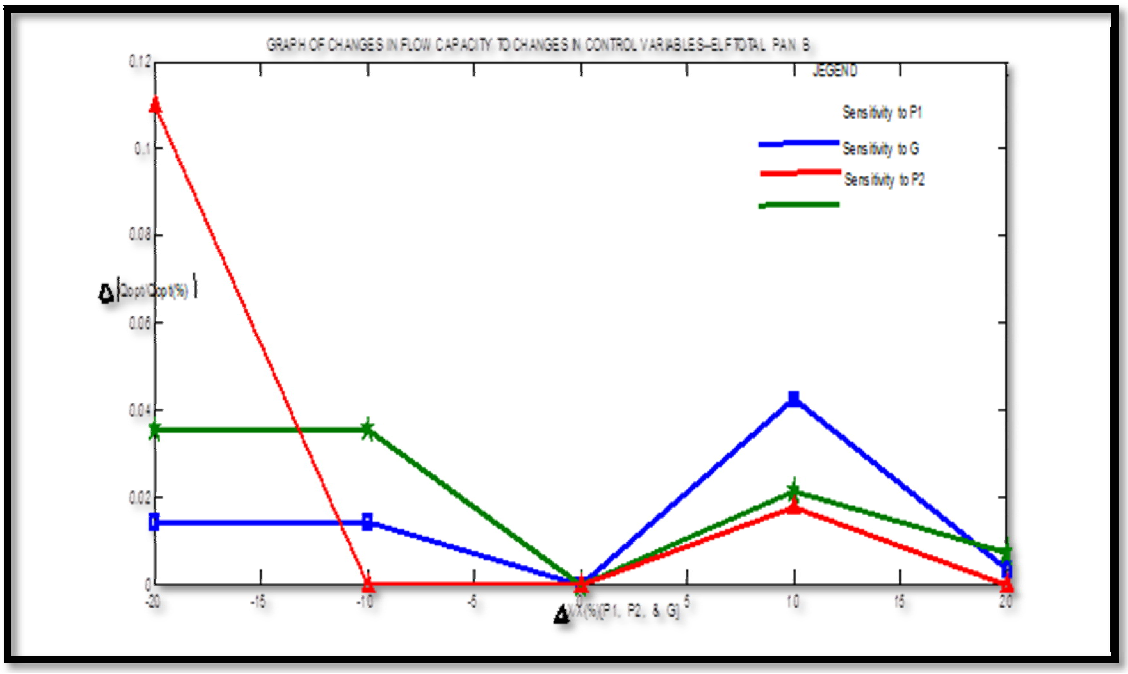

Figure 1b: Graph of Changes in Flow Capacity to Changes in Control Variables: ElfTotal Nig. Ltd—Panhandle-B

PIPELINE : SHELL PETROLEUM DEVELOPMENT COMPANY : OPTIMIZATION MODEL : PANHANDLE A								
BASE PARAMETERS :		Upstream Pressure, P_1=81 bar; Downstream Pressure, P_2=63bar						
		Operational Flow Capacity, Q=1.8m^3/s; Optimal Flow Capacity, Q_{opt}=1.9443m^3/s						
		Specific Gravity, G=0.6978; Flow Compressibilty Factor, Z=1.241						
		Line length, L=116km; Line Diameter, D=36" (0.9144m)						
$\Delta P_1/P_1$ (%)	-20	-10	0	4	10	20		
P_{1new}(bar)	67.33	75.69	81	84.24	89.1	97.2		
$I\Delta Q_{opt}/Q_{opt}$ (%)I	0.9361	0.0926	0	0.0962	0.1132	0		
$\Delta P_2/P_2$ (%)	-20	-10	0	4	10	20		
P_{2new}(bar)	50.4	56.7	63	65.52	69.3	75.6		
$I\Delta Q_{opt}/Q_{opt}$ (%)I	0.00514	0.1206	0	0.1029	0.00514	0.0103		
$\Delta G/G$ (%)	-20	-10	0	4	10	20		
G_{new}	0.5582	0.628	0.6978	0.7257	0.7676	0.8374		
$I\Delta Q_{opt}/Q_{opt}$ (%)I	0.159	0.0106	0	0.0106	0.0053	0.00159		

Table 2a : Results Showing Sensitivities of Optimal Flow Capacities to Variability In Operating Condition: Shell—Panhandle-A

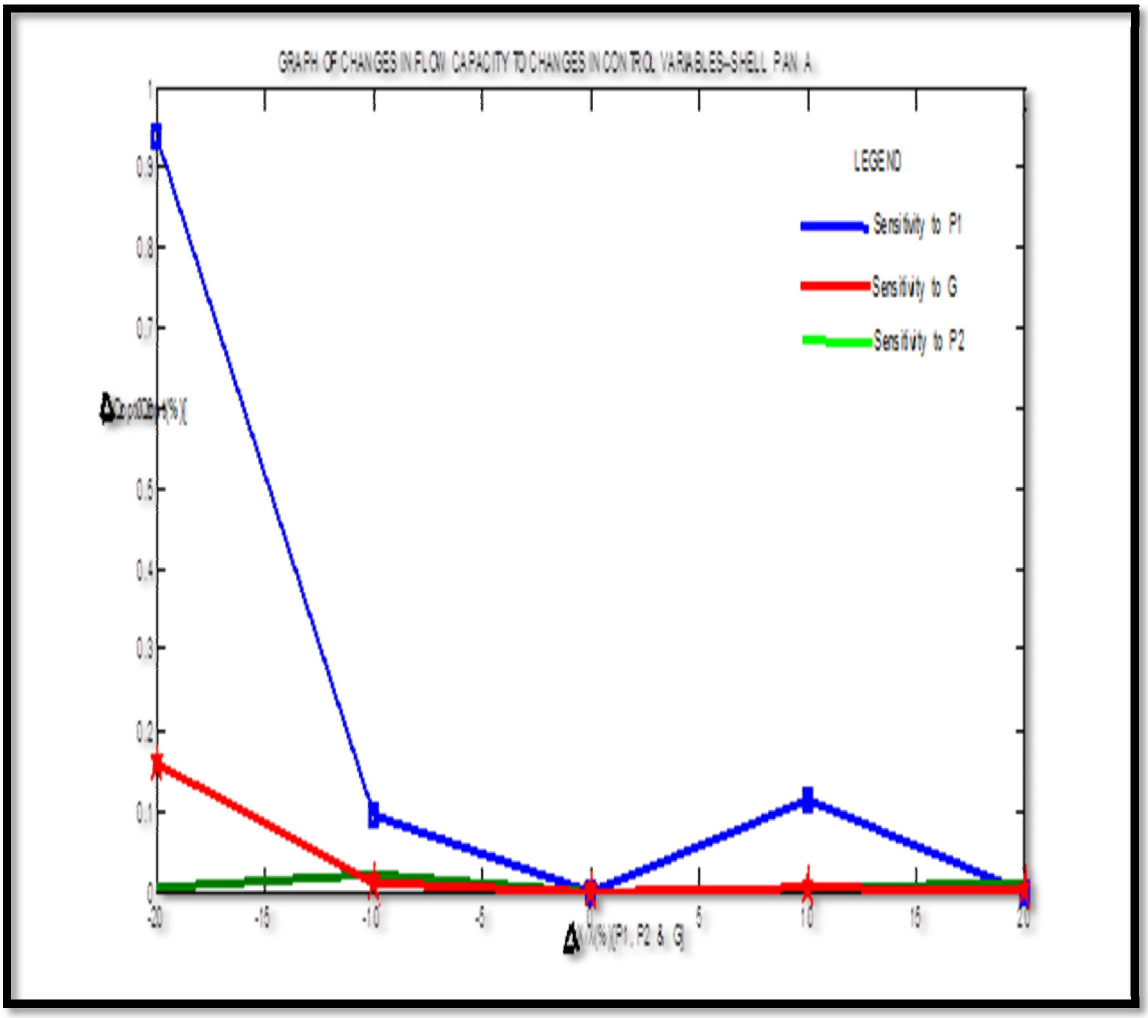

Figure 2a: Graph of Changes in Flow Capacity to Changes in Control Variables: Shell Petroleum Development Company—Panhandle-A

PIPELINE : SHELL PETROLEUM DEVELOPMENT COMPANY : OPTIMIZATION MODEL : PANHANDLE B						
BASE PARAMETERS :		Upstream Pressure, P_1=81 bar; Downstream Pressure, P_2=63bar				
		Operational Flow Capacity, Q=1.8m^3/s; Optimal Flow Capacity, Q_{opt}=3.3058m^3/s				
		Specific Gravity, G=0.6978; Flow Compressibilty Factor, Z=1.241				
		Line length, L=116km; Line Diameter, D=36" (0.9144m)				
$\Delta P_1/P_1$ (%)	-20	-10	0	4	10	20
P_{1new}(bar)	67.33	75.69	81	84.24	89.1	97.2
$I\Delta Q_{opt}/Q_{opt}$ (	0.0151	3.161	0	0.0962	0	0.185
$\Delta P_2/P_2$ (%)	-20	-10	0	4	10	20
P_{2new}(bar)	50.4	56.7	63	65.52	69.3	75.6
$I\Delta Q_{opt}/Q_{opt}$ (	0.0091	0.1206	0	0.1029	0.00303	0.0091
$\Delta G/G$ (%)	-20	-10	0	4	10	20
G_{new}	0.5582	0.628	0.6978	0.7257	0.7676	0.8374
$I\Delta Q_{opt}/Q_{opt}$ (	0.00605	0.00303	0	0.0106	0.0121	0.00605

Table 2b : Results Showing Sensitivities of Optimal Flow Capacities to Variability in Operating Condition: Shell—Panhandle-B

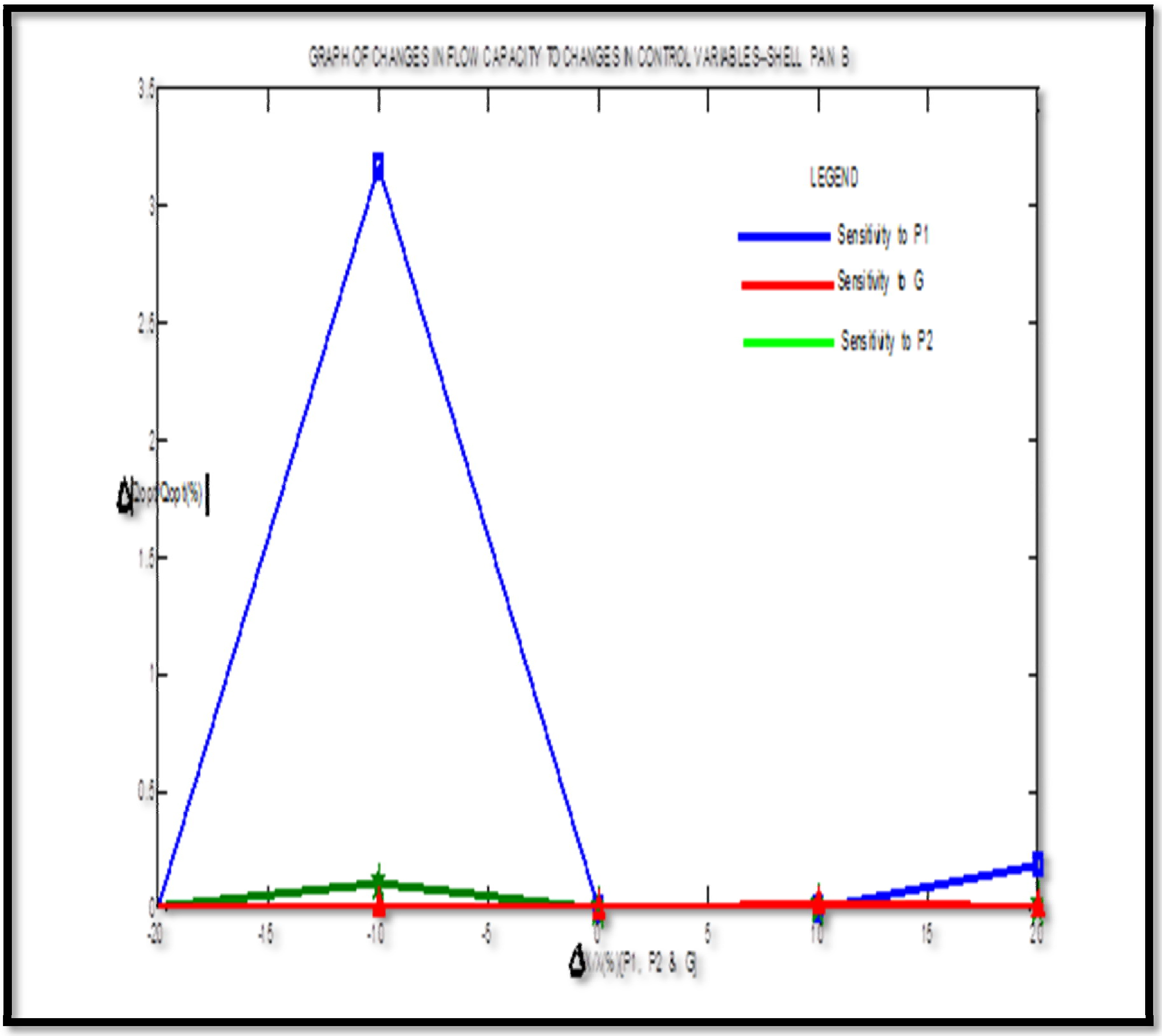

Figure 2b: Graph of Changes in Flow Capacity to Changes in Control Variables: Shell Petroleum Development Company—Panhandle-B

PIPELINE : AGIP NIG. LTD ; OPTIMIZED MODEL : PANHANDLE A								
BASE PARAMETERS :		Upstream Pressure, P_1=84.1 bar; Downstream Pressure, P_2=63bar						
		Operational Flow Capacity, Q=1.8m^3/s; Optimal Flow Capacity, Q_{opt}=1.8864m^3/s						
		Specific Gravity, G=0.6571; Flow Compressibilty Factor, Z=1.0						
		Line length, L=150km; Line Diameter, D=36" (0.9144m)						
$\Delta P_1/P_1$ (%)	-20	-10	0	0.5	10	20		
P_{1new}(bar)	67.33	75.69	84.1	84.52	92.51	104.2		
$I\Delta Q_{opt}/Q_{opt}$ (%)I	0.00053	0.0106	0	0.0159	0.0159	0.556		
$\Delta P_2/P_2$ (%)	-20	-10	0	0.5	10	20		
P_{2new}(bar)	50.4	56.7	63	63.325	69.3	75.6		
$I\Delta Q_{opt}/Q_{opt}$ (%)I	0.0265	1.665	0	0.0091	0	0.0159		
$\Delta G/G$ (%)	-20	-10	0	0.5	10	20		
G_{new}	0.53	0.592	0.666	0.66933	0.733	0.798		
$I\Delta Q_{opt}/Q_{opt}$ (%)I	0.0053	0.000265	0	0.0106	0.00848	0.0106		

Table 3a : Results Showing Sensitivities of Optimal Flow Capacities to Variability In Operating Condition: Agip Nig. Ltd—Panhandle-A

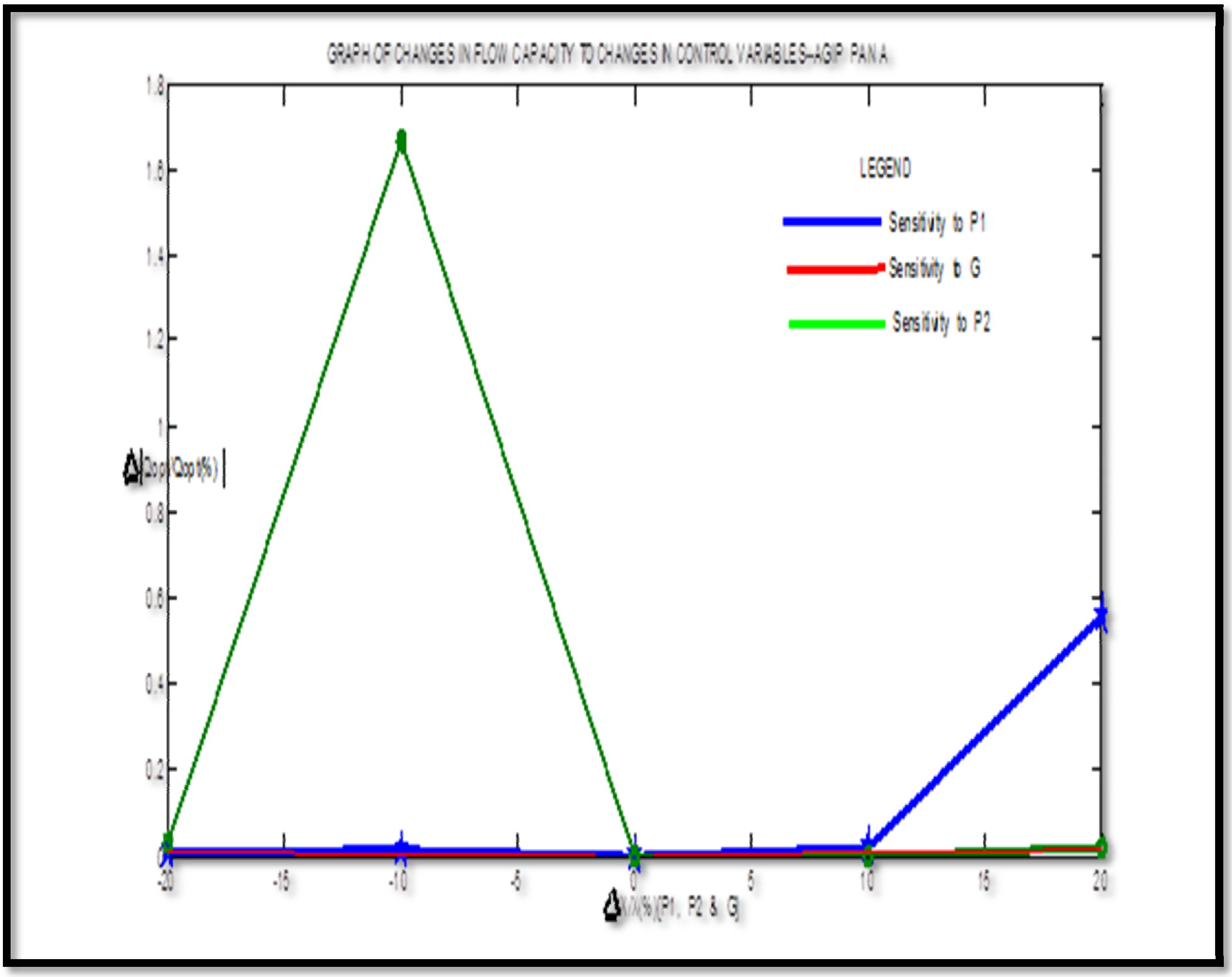

Figure 3a: Graph of Changes in Flow Capacity to Changes in Control Variables: Agip Nig. Ltd-Panhandle-A

PIPELINE : AGIP NIG. LTD ; OPTIMIZED MODEL : PANHANDLE B								
BASE PARAMETERS :		Upstream Pressure, P_1=84.1 bar; Downstream Pressure, P_2=63bar						
		Operational Flow Capacity, Q=1.8m^3/s; Optimal Flow Capacity, Q_{opt}=2.81932m^3/s						
		Specific Gravity, G=0.6571; Flow Compressibilty Factor, Z=1.0						
		Line length, L=150km; Line Diameter, D=36" (0.9144m)						
$\Delta P_1/P_1$ (%)	-20	-10	0	10	20			
P_{1new}(bar)	67.33	75.69	84.1	92.51	104.2			
$\lvert\Delta Q_{opt}/Q_{opt}$ (%)$\rvert$	0.0206	0.0163	0	0.0326	0.0231			
$\Delta P_2/P_2$ (%)	-20	-10	0	10	20			
P_{2new}(bar)	50.4	56.7	63	69.3	75.6			
$\lvert\Delta Q_{opt}/Q_{opt}$ (%)$\rvert$	0.0277	0.0184	0	0.0209	0.0124			
$\Delta G/G$ (%)	-20	-10	0	10	20			
G_{new}	0.53	0.592	0.666	0.733	0.798			
$\lvert\Delta Q_{opt}/Q_{opt}$ (%)$\rvert$	2.39	1.642	0	0.0213	0.00426			

Table 3b : Results Showing Sensitivities of Optimal Flow Capacities to Variability in Operating Condition: Agip Nig. Ltd—Panhandle-B

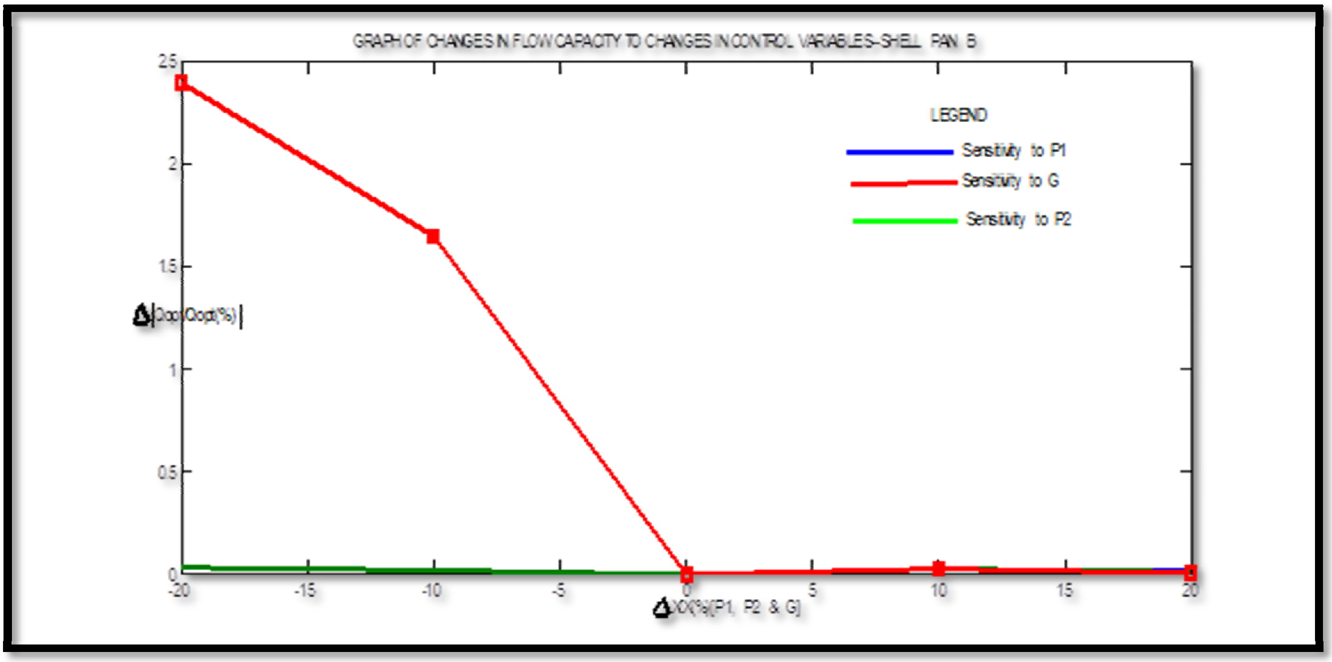

Figure 3b: Graph Of Changes in Flow Capacity to Changes in Control Variables: Agip Nig. Ltd-Panhandle-B

PIPELINE : NIGERIA GAS COMPANY (NGC) EASTERN DIVISION; OPTIMIZED MODEL : PANHANDLE A								
BASE PARAMETERS :		Upstream Pressure, P_1=80.6 bar; Downstream Pressure, P_2=64bar						
		Operational Flow Capacity, Q=1.8m^3/s; Optimal Flow Capacity, Q_{opt}=1.9382m^3/s						
		Specific Gravity, G=1.326; Flow Compressibilty Factor, Z=1.383						
		Line length, L=122km; Line Diameter, D=36" (0.9144m)						
$\Delta P_1/P_1$ (%)	-20	-10	0	5	10	20		
P_{1new}(bar)	64.48	72.54	80.6	84.63	88.66	96.72		
$\lvert\Delta Q_{opt}/Q_{opt}$ (%)$\rvert$	1.0003	0.0361	0	0.155	0.0103	0.372		
$\Delta P_2/P_2$ (%)	-20	-10	0	5	10	20		
P_{2new}(bar)	50.4	57.6	64	67.2	70.4	76.8		
$\lvert\Delta Q_{opt}/Q_{opt}$ (%)$\rvert$	0.00413	0.0243	0	0.0248	0.0206	0.0381		
$\Delta G/G$ (%)	-20	-10	0	5	10	20		
G_{new}	1.061	1.193	1.326	1.3928	1.459	1.591		
$\lvert\Delta Q_{opt}/Q_{opt}$ (%)$\rvert$	0	0.464	0	0.361	0	0.0464		

Table 4a : Results Showing Sensitivities of Optimal Flow Capacities to Variability in Operating Condition: NGC Eastern Division Nig. Ltd—Panhandle-A

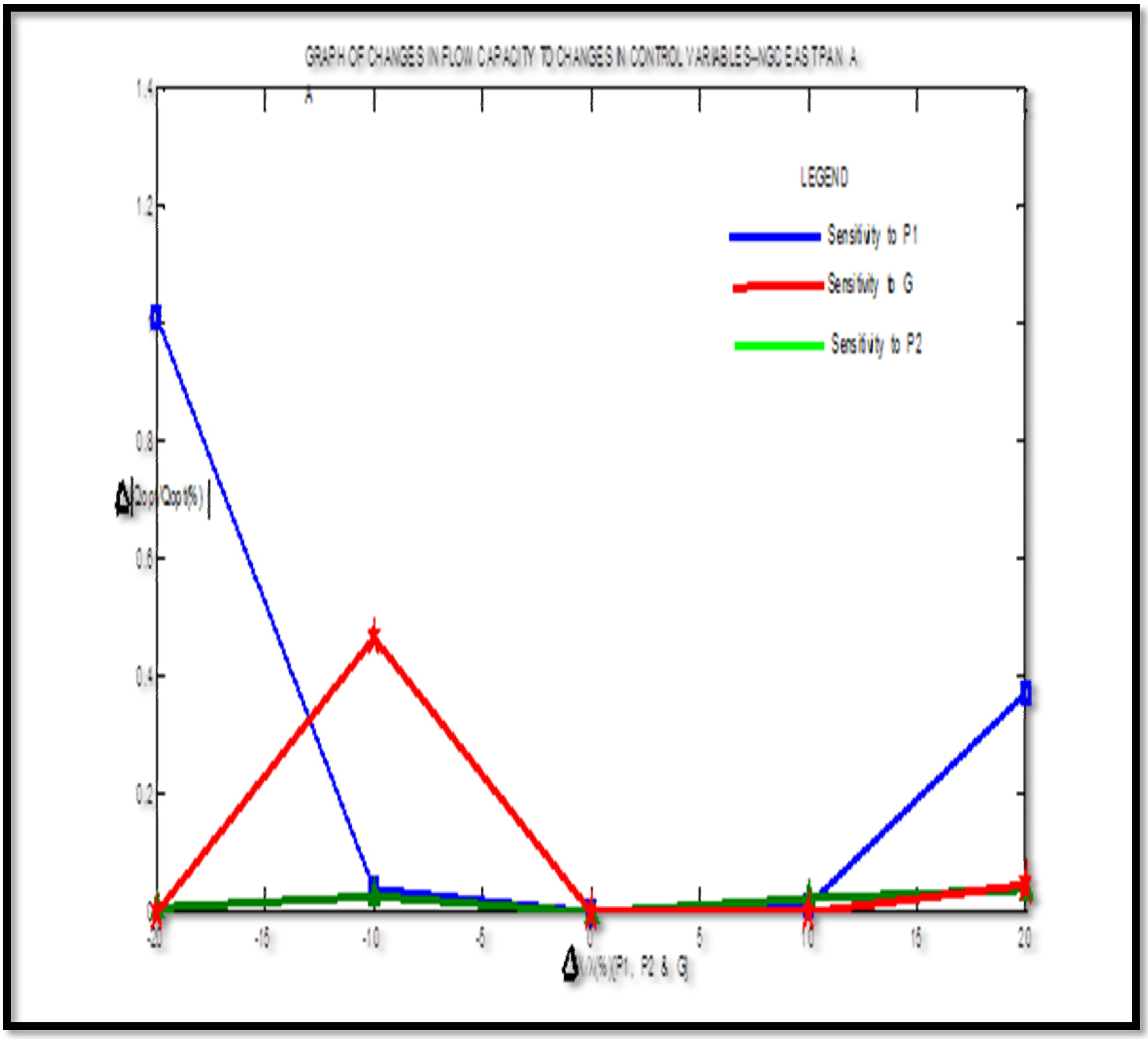

Figure 4a: Graph of Changes in Flow Capacity to Changes in Control Variables: Nigeria Gas Company (Eastern Division)-Panhandle-A

PIPELINE : NIGERIA GAS COMPANY (NGC) EASTERN DIVISION; OPTIMIZED MODEL : PANHANDLE B								
BASE PARAMETERS :	Upstream Pressure, P_1=80.6 bar; Downstream Pressure, P_2=64bar							
		Operational Flow Capacity, Q=1.8m^3/s; Optimal Flow Capacity, Q_{opt}=3.3008.m^3/s						
		Specific Gravity, G=1.326; Flow Compressibilty Factor, Z=1.383						
		Line length, L=122km; Line Diameter, D=36" (0.9144m)						
$\Delta P_1/P_1$ (%)	-20	-10	0	10	20			
P_{1new}(bar)	64.48	72.54	80.6	88.66	96.72			
$\|\Delta Q_{opt}/Q_{opt}$ (%)$\|$	7.11	7.13	0	0.0673	0.5373			
$\Delta P_2/P_2$ (%)	-20	-10	0	10	20			
P_{2new}(bar)	50.4	57.6	64	70.4	76.8			
$\|\Delta Q_{opt}/Q_{opt}$ (%)$\|$	0	0.00909	0	0.00969	0.0348			
$\Delta G/G$ (%)	-20	-10	0	10	20			
G_{new}	1.061	1.193	1.326	1.459	1.591			
$\|\Delta Q_{opt}/Q_{opt}$ (%)$\|$	3.7	0.0027	0	0.0158	0.0998			

Table 4b : Results Showing Sensitivities of Optimal Flow Capacities to Variability In Operating Condition: NGC Eastern Division Nig. Ltd—Panhandle-B

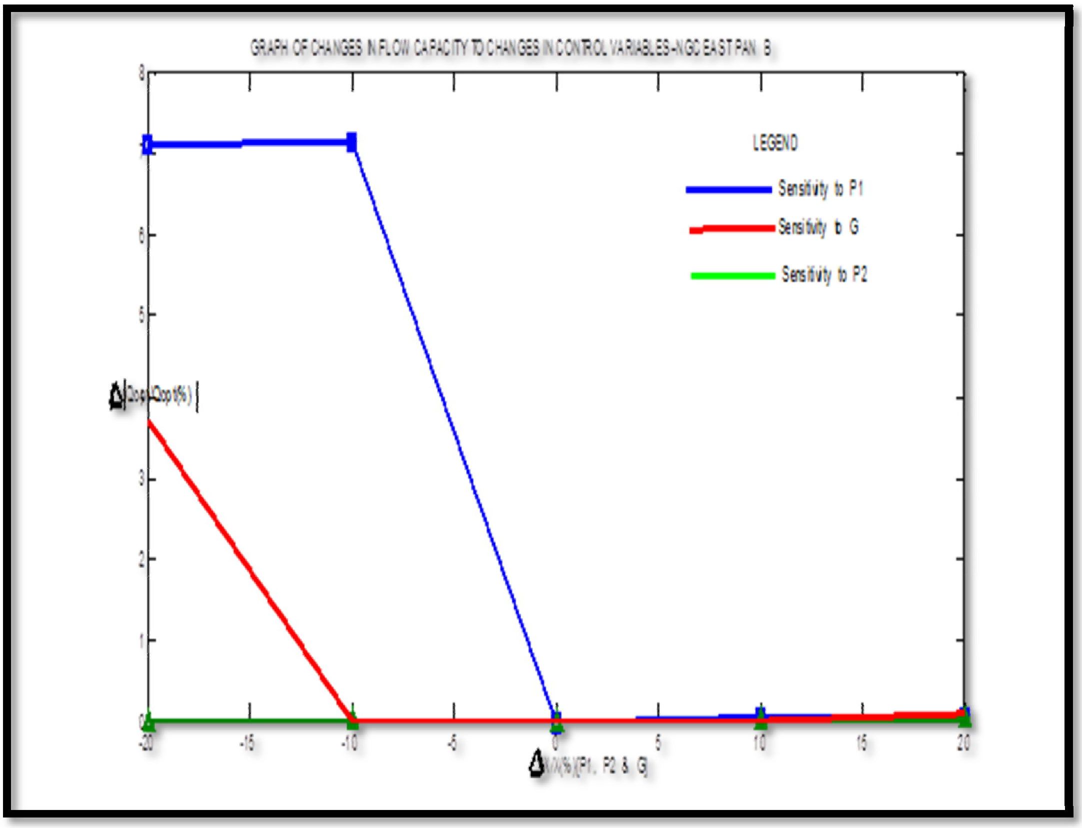

Figure 4b: Graph of Changes in Flow Capacity to Changes in Control Variables: Nigeria Gas Company (Eastern Division)-Panhandle-B

Three control variables were kept in view in the determination of the sensitivity of the optimal flows to three control variables namely upstream pressure, downstream pressure and gas specific gravity. The three control variables were adjusted within the limit of ±20 %. Percentage change in optimal flow was determined for all the case study companies with respect to transformed Panhandle-A and Modified Panhandle-B equations. The percentage in the optimal flow capacity was insignificant. This gives credence, authenticates and establish the stability of the results of optimization of flow capacities carried out in the researcher's previous works. The Panhandle-A flow model yielded lower values of changes in optimal flow capacities upto to the limit of 1.0 %. In comparison, the Panhandle-B flow model gave sensitivities upto a maximum of 9.0 %, for all the Pipelines covered in the study and the flow control variables.

The operating threshold based on off design analysis for ElfTotal Nig. Ltd and Shell Petroleum Development Company (Tables 6 to 10) confirmed that the line flow throughput could be varied within 1 m^3/s to 6.5 m^3/s. The nominal line diameter could be fixed within 30" and 65". These conditions are possible within the limit of pressure variation in the range of 30 bar to 170 bar at stream temperature of 40 ^0C. These findings are so vital in establishing the design, construction and operation of our new generation gas pipeline network system.

D(m)	P_1(bar)	P_2(bar)	ΔP_{opt}	Q_{opt}	L(Km)
(36")0.9144m	64	48	15.48	1.89	134
	84.1	63	12.34	2.63	
	84.1	71	12.91	1.907	
	110	80	7.93	1.52	
	130	100	11.06	1.89	
	150	125	10.33	1.89	
	170	140	6.56	1.52	
43"(1.0922)	50	30	16.97	2.63	
	64	48	14.87	3.25	
	84	63	12.35	2.64	
	110	80	11.01	2.63	
	130	100	10.19	2.63	
	150	125	9.54	2.64	
	170	140	9.22	2.64	
50"(1.27)	64	48	13.33	3.52	
	84.1	63	11.59	3.51	
	110	80	10.38	3.51	
	130	100	9.64	3.51	
	150	125	9.03	3.52	
	170	140	8.69	3.51	
65"(165.1)	64	48	10.55	5.94	
	84.1	63	11.06	5.94	
	110	80	9.96	5.94	
	130	100	9.28	5.95	
	150	125	8.72	5.94	
	170	140	8.41	6.46	

Table 6 : ElfTotal Optimised Panhandle- A Operating Threshold

D(m)	P_1(bar)	P_2(bar)	ΔP_{opt}	Q_{opt}	L(Km)
36"(0.9144)	50	30	10.791	2.7196	
	64	48	10.785	2.7189	
	84	63	9.89	2.7189	
	110	80	10.7875	2.71918	
	130	100	10.7897	2.7195	
	150	125	10.7875	2.71918	
	170	140	10.7841	2.71875	
43"(1.0922)	50	30	10.3947	3.72097	
	64	48	10.4077	3.7209	
	84	63	10.40767	3.72092	
	110	80	10.356	3.7118	
	130	100	10.40794	3.72096	
	150	125	10.409	3.7212	
	170	140	10.4262	3.721	
50"(1.27)	50	30	10.04991	4.9761	
	64	48	10.049939	4.976092	
	84	63	10.04984	4.97609	
	110	80	10.049939	4.9760913	
	130	100	10.04994	4.976092	
	150	125	10.049942	4.976092	
	170	140	10.049941	4.976092	

Table 7 : ElfTotal Optimised Panhandle- B Operating Threshpld

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	

Table 8 : 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	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	

Table 9 : Shell Optimised Panhandle- B Operating Threshold

1.3. Recommendation for Future Research

The results of the optimal flow sensitivities should be applied in the design, construction and operation of our new generation gas pipeline network system in Nigeria and around the world.

1.4. Conclusion

The results of the sensitivity of optimal flow validates optimal flow capacity in the previous works. The sensitivity results confirmed that the percentage change in the optimal flow was so insignificant; confirming the reliability and stability of the optimal values of flow throughput. The researcher strongly advice that the results of the optimal flow sensitivity be in-cooperated in the design and installation criteria of our new breed of gas pipeline network system.

Nomenclature

V_L, V_G – liquid and gas local velocities (m/s)

$\overline{V}_M$ -- mixture mean flow velocity (m/s)
μ_G—absolute gas viscosity (Pas)
A, B, C—virial coefficients (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
$\overline{V}_L$, $\overline{V}_G$ – 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)

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