Subsea Pipeline Design for Natural Gas Transportation: A Case Study of Côte D'ivoire's Gazelle Field

S. A. Marfo[1*], P. Opoku Appau[2], L. A. A. Kpami[1]

[1]*Department of Petroleum Engineering, University of Mines and Technology, Tarkwa, Ghana.*

[2]*Research Institute of Enhanced Oil Recovery, China University of Petroleum (Beijing), P. R. China.*

*****Corresponding Author:** S. A. Marfo, *Department of Petroleum Engineering, University of Mines and Technology, Tarkwa, Ghana.*

Abstract: *Pipeline plays a vital role in modern civilisation as it provides the needed fuels for sustaining imperative functions such as power generation, heating supply, and transportation. The cost of installing underwater pipelines is a significant factor in the economics of offshore natural gas exploitation. Proper design of these networks can facilitate the economic integration of newly discovered fields into the gathering system and result in lower prices to the consumer. This study employs PIPESIM software to design a subsea pipeline for transportation of natural gas from Gazelle Field in Côte d'Ivoire to a processing platform located 30 km and to predict the conditions under which hydrate will form so as to be avoided. The design comprised of two risers and one flowline. Hydrate was anticipated to form at a temperature of 65 °F for an arrival pressure of 800 psia. For optimal insulation thickness to be achieved in the design, different insulation materials and thicknesses were simulated. The insulation thickness for the flowline was determined to be 0.75 in. with specific pipe size of 10 in. to satisfy the arrival pressure condition. The gas composition and flow line thermal insulation are of prime importance within a design process to guarantee that pipeline operate normally.*

Keywords: *Flow Assurance, Flowline, Hydrate, Natural Gas, Phase Envelope, PIPESIM*

1. INTRODUCTION

Natural gas which is commercially extracted from oil fields and natural gas fields has emerged as a cheaper and efficient source of energy. It has become a fuel of choice for various uses. It is used extensively by domestic consumers for cooking and heating, by power producers for generating electricity and by petrochemical and fertilizer industries as both fuel and feedstock [1, 2]. A major challenge associated with the extraction and use of the natural gas is the problem of transporting. Therefore there is the need to effectively transport gas from the gas fields to the processing units and from the processing unit to the end users. Over the years, pipelines have shown to be the safest, most efficient and economical mode of transporting natural gas [3]. Pipelines are lifeline of the global oil and gas industry, providing economic, reliable means to transport oil and natural gas from upstream production to downstream refineries, power stations and market [4]. Generally defined as a long line of connected segment of pipe, with pumps, valves and other equipment needed for operating the system, pipelines have been used for transportation of liquids and gases for thousands of years [5]. Piping systems are like arteries and veins; they carry the lifeblood of modern civilisation [6]. In developed nations, gas pipelines have extensively been constructed to supply gas from oil fields to processing units and from these processing units to factories and homes where they are consumed. Pipelines are vitally important to the economic wellbeing and security of most nations [7].

Produced natural gas stream from the reservoir is always saturated with water and one of the problems associated with its transmission especially in subsea pipeline is the formation of hydrate which is defined as crystalline structures between water and hydrocarbon [8]. The design of subsea pipeline known as pipeline that is laid on the seabed or below it inside a trench need to take into account a large number of factors [9]. Hydrate formation in subsea pipeline is a major problem that arises due to temperature drop and other thermodynamic changes during production [10, 11]. The pipeline is exposed to the cooling sea current, thus the gas inside the pipeline is cooled down to temperatures that

favours hydrate formation. Therefore preventing hydrate formation in subsea pipelines to assure the smooth operation of pipeline is of paramount importance [12].

Insulating subsea pipeline is essential to avoid hydrate formation [13]. Insulation provide hydrate control by maintaining temperature above the hydrate condition, it also extends the cool down time before reaching hydrate formation temperature [14, 15]. Oil and gas pipelines are insulated mainly to conserve energy by reducing heat loss and to facilitate the temperature control process [16]. The need to keep the fluids in the pipeline at a temperature higher than the ambient temperature could exist for reasons which include flow assurance [17]. The problem of design procedure is to find a pipeline configuration and size within the constraints which is safe and economical [18]. This paper therefore aims at developing a subsea pipeline that deals with problems that arises during transportation of natural gas from a production field to a processing platform, using Gazelle Field in Côte d'Ivoire as a case study.

1.1. Background Study

The Gazelle oil and gas field is located in Block CI-202, covering an area of 707 km^2 located just 30 km to the southeast of Abidjan, the primary commercial centre of Côte d'Ivoire, extending from the coastline to water depths ranging between 30 m and 50 m in the offshore Ivorian Basin. The Gazelle Field was discovered in 1977 by Esso and tested a mixture of gas and oil over a number of tests. A total of seven appraisal wells were drilled in 1977-2012 with Esso drilling three. The Gazelle oil and gas Field is expected to hold 92 Bcf of gas. The block lies in water depths ranging from 0 to 1000 m, with most of the block situated in water depths of less than 100 m. The block is a highly prospective exploration license with 6 oil and gas discoveries. It has a significant database of block-wide high quality 3D seismic, 15 wells and over 20 production tests, some of which have produced gas at up to 48 MMscfd and oil at over 5000 bopd [19].

Figure1. *Ivorian Basin showing Gazelle Oil and Gas Field (Anon, 2013)*

The Gazelle oil and gas field is owned and operated by Vioco Petroleum Limited (formerly Railto Energy), which holds an 87 % working interest, while the remaining 13 % share in the field is held by state-owned oil company Petroci (Société Nationale d'Opérations Pétrolières de la Côte d'Ivoire). The field development plan and gas agreement consisted of a fixed production platform at the Gazelle Field with separate oil and gas pipelines from the platform to shore. The oil and gas production will be processed and exported via bundled pipelines to existing onshore infrastructure, located 19 miles (30 km) to the northwest of CI-202. The platform will have a production capacity of up to 40,000 bopd and 230 MMcf/d to allow for further infill drilling at Gazelle and the tie-back of existing satellite fields [20, 21].

The overall Gazelle field development concept is based on transporting Gazelle gas to an onshore gas plant located at the east of Grand Bassam for processing, from where it will be transferred to an Independent Power Plant (IPP) which will be contracted by CI-Energies to produce electricity for the National Grid. The Gazelle well stream will be directly transferred to shore through a multiphase pipeline to the onshore processing plant located to the East of Grand Bassam. After treatment, the Gazelle gas feeds a power plant located a short distance from the Vioco plant [22].

1.2. Flow Assurance

Flow assurance deals with the process of ensuring the safe transport of reservoir fluids right from the production point to the users' end in an economical manner [23]. In subsea transportation of natural gas, flow assurance is considered crucial because of anticipated high pressure and low temperature

[10]. This process therefore requires a comprehensive knowledge about multiphase flow of fluids and the factors that can have an impact on these fluids. As fluids flow from one point to the other, there are also the risk of reduction in the fluid parameter, in other sense flow assurance which can result in the deposition of hydrates, wax, asphaltene and scale in the flowline. Due to the nature of the subsea environment, it is imperative to quantify the potential and extent of the problems that arises during the flow of fluid in order to mitigate the problems [24]. Although there are various problems that limit the efficiency of flow assurance, however, this paper focuses on hydrate formation and its implication on the fluid being transported.

1.2.1. Hydrate Formation in Pipeline

The oil industry today is forced into less accessible areas to acquire more oil to satisfy the growing energy market. The subsea environment which involves low temperatures as well as high pressures, high water cuts, and longer transfer times provide conditions that are ideal for hydrates and wax formation, and other solids deposits. These are the fundamental impediments to production of oil and gas through long distance subsea pipelines [25]. In deepwater oil exploration wells located far from platforms, crude oil often has to be transported over long distances in subsea pipelines [26]. The oil is cooled on its way to the destination due to heat transfer through the pipelines walls with the surrounding sea water. Temperature related transportation problems can take place if the pipelines are not insulated leading to rapid temperature drop. This may lead to the precipitation of asphaltenes and/or paraffin wax and the formation of hydrates [27]. Gas hydrates form in pipelines and production facilities at elevated pressures and reduced temperatures resulting to blocked pipeline, high removal cost and environmental risks. Offshore production of oil and gas operations are exposed to certain pressure and temperature conditions which can lead to gas hydrate formation and severe flow assurance problems in pipelines and other facilities. Gas hydrate formation is undesirable in oil and gas pipelines making their prevention necessary when they are formed [28].

1.2.2. Hydrate Mitigation and Remediation

For stable hydrate crystals to form in oil and gas production systems, four essential elements must be present; supply of hydrate forming guest molecules such as N_2, CO_2, H_2S, CH_4, C_2H_8, and other hydrocarbon molecules; water; low temperature and high pressure [29]. Strategies for hydrate mitigation and remediation often modify one or more of these elements to destabilise the hydrate and thus remove the problem. The various methods of hydrate control presented by several researchers [30-34] include controlling pressure outside hydrate envelope; temperature control by passive or active insulation (such as Direct Electrical Heating - DEH); removing supply of water by dehydration or separation; removal of supply of hydrate formers by gas-liquid separation; and injection of chemical inhibitors such as methanol and ethanol among others.

1.3. Pipeline Design Consideration

1.3.1. Factors Influencing Pipeline Design

Many factors must be considered in the design of long distance gas pipeline. These include the nature of the gas to be transmitted, the length of the line, the type of terrain to be crossed, and maximum elevation of route [35]. When natural gas is produced from wells, it is treated, then transported via transmission pipeline to distribution network systems, and to the consumers [36]. Gas pipelines require special attention over and above the normal design requirements for liquids because of the vast quantity of stored energy in the pipeline steel due to the compressibility of gas. Therefore, in order to achieve the optimum operation and management for a pipeline system, complex engineering and technological studies must be conducted to determine pipeline steel material and size selection, pressure and temperature requirement, flow velocity, coating and cathodic protection design [37].

1.3.2. Offshore Pipelines

Offshore pipeline design differs primarily in the requirements of the environment and the installation process. Pipe used in offshore applications is subjected to high bending stresses potential crushing forces, especially for pipes installed in deep water and a low-density environment. Until recently, the pipeline size was severely limited, but technological developments and improved construction methods have enabled offshore pipelines to continue to increase in size and capacity. Pipelines up to 28-in. diameter are now installed in the deep-water applications up to 7,000 ft of water [38].

1.3.3. Parameters Required in Pipeline Design

For gas flow in pipes, three simplified derivative equations can be employed to calculate the flow namely, Weymouth, Panhandle and the Spitzglass equations. All three equations are effective, however, the accuracy and applicability of each falls within certain ranges of flow and pipe diameter. The Weymouth equation is recommended for smaller-diameter pipe (generally, 12 in. and less), shorter lengths of segments (< 20 miles) within production batteries and for branch gathering lines, medium- to high-pressure (+/–100 psig to > 1,000 psig) applications, and a high Reynolds number. Panhandle equation on the other hand is recommended for 12-in. pipe diameter and greater. It is also recommended for long runs of pipe (> 20 miles) such as cross-country transmission pipelines and for moderate Reynolds numbers. The Spitzglass equation is recommended for low-pressure vent lines < 12 in. in diameter (ΔP < 10% of P_1) [39]. In this paper, all three equations were used at a specific periods throughout the flow of fluid in the pipeline.

Weymouth equation

$$Qg = 1.1 d^{2.67} \left[\frac{P_1^2 - P_2^2}{LSZT_1} \right]^{\frac{1}{2}}$$

[1]

Panhandle equation

$$Qg = 0.028E \left[\frac{P_1^2 - P_2^2}{S^{0.961} ZTL_m} \right]^{0.51} d^{2.51}$$

[2]

Spitzglass equation

$$Qg = 0.09 \left[\frac{\Delta hwd^5}{SL \left(1 + \frac{3.6}{d} + 0.03d \right)} \right]^{\frac{1}{2}}$$

[3]

Reynolds number and Moody friction factor

The Reynolds number is a dimensionless parameter that is useful in characterising the degree of turbulence in the flow regime and is needed to determine the Moody friction factor. The Moody friction factor f is a function of the Reynolds number and the roughness of the internal surface of the pipe and is given by Friction-factor chart. The Moody friction factor is dependent on the characteristic of the flow in the pipe. For laminar flow, where Re is < 2,000, there is little mixing of the flowing fluid, and the flow velocity is parabolic; the Moody friction factor is expressed as $f = 64/Re$. For turbulent flow, where Re > 4,000, the flow mixes completely producing uniform velocity profile; and f depends on Re and the relative roughness (ε/D) (ratio of absolute roughness, ε to the pipe internal diameter, D) [39].

The general equation for Reynolds numbers is expressed as:

$$\text{Re} = \frac{\rho v d}{\mu}$$

[4]

The Reynolds number for liquids can be expressed as:

$$\text{Re} = \frac{92.1(SG)Q_l}{d\mu}$$

[5]

The Reynolds number for gases can be expressed as:

$$\text{Re} = 20,100 \frac{Qg.S}{d\mu}$$

[6]

Pressure drop for liquid flow

$$d^5 = (11.5 \times 10^{-6}) \frac{fLQ_l}{\Delta P}$$

[7]

Pressure drop for gas flow

The general equation for calculating gas flow is stated as:

$$W^2 = \left[\frac{144 g A^2}{V_1 \left(\dfrac{fL}{d} + 2\log_e \dfrac{P_1}{P_2} \right)} \right] \times \left[\frac{(P_1)^2 - (P_2)^2}{P_1} \right] \qquad [8]$$

For practical pipeline purposes, equation 8 can be simplified to:

$$P_1^2 - P_2^2 = 25.5 + \left(\frac{SQgZTfL}{d^5} \right)$$

[9]

The above equation assumes no work done; steady-state flow and *f*=constant and is as a function of the length. Also, since equation 8 was simplified certain assumptions were made in the application of each of the three equations (7, 8 and 9). The equations used in this paper were obtained from already established pressure drop gas flow equations [39].

1.4. Pipeline Insulation

Generally, insulations are defined as those materials or combinations of materials which retard the flow of heat energy by conserving energy by reducing heat loss or gain; facilitate temperature control of process and prevent vapour flow and water condensation on cold surfaces [40]. Insulating pipes and subsea structures is essential to avoid the possibility of wax and hydrate formation. The most commonly used materials in subsea thermal insulation are polyurethanes and polypropylenes, due to their suitability for large scale production, availability of raw materials and system cost [41]. Oil and gas field pipelines are insulated mainly to conserve heat. The need to keep the product fluids in the pipeline at a temperature higher than the ambient temperature could exist, for reasons which include flow assurance [17]. Thermal insulation is necessary to avoid formation of hydrate plugs and wax build-up in subsea structures. Without thermal insulation cold seawater rapidly cools down the fluid, forming hydrate/wax blockages making it impossible for a safe flow. Thermal insulation materials are applied in order to prevent formation of these blockages during a shutdown scenario or during normal operations [42].

There are some specific requirements to be fulfilled for selecting a suitable insulation material and these include; low thermal conductivity, high heat capacity, high density, ability to withstand high hydrostatic pressure, economical, easy to install and maintain [43]. According to Sadafule *et al.* (2014), there are several types of insulation materials available for Pipe-in-Pipe (PiP) design which includes Polypropylene (PP), Polypropylene-Foam (PPF), Polypropyene-Reinforced Foam Combination (RPPF), Polyurethane (PU), Polyurethane-Syntactic (SPU), and Polyurethane-Foam (PUF). They are suggested to install multi-layer passive thermal insulation in order to maintain pipeline temperature much longer [27].

2. RESOURCES AND METHODS USED

This study required collection of data on operating conditions. Secondary data on gas composition, properties and gas entry pressure were collected from Vioco Petroleum Limited, Côte d'Ivoire. The PIPESIM software was the facilities package for design, simulation and optimisation. This section gives details of the procedure used in developing the application and the application functional test carried.

2.1. The Main application form

The main application form is a multi-document form. Multi-document form are windows applications that can hold more than one window. The interfaces are designed as parents and children, that is to say some interfaces depend on others. Hence the main form is the parent form which holds all other forms. Figure 2 shows the main application form. This form also holds the menu bar and the toolbar.
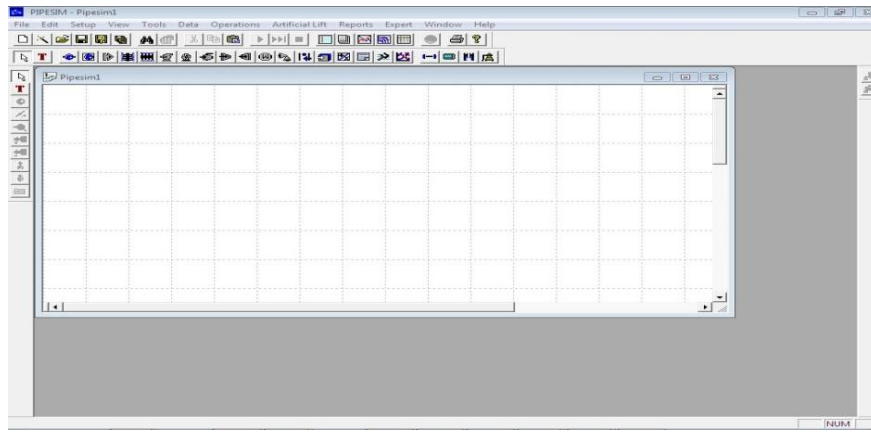
Figure2. *Main Application Form*

2.2. The Child Form

Child forms are the windows or a form launched within the main form and is dependent on the main form. These are some of the child form available in the software:

2.2.1. Project Creation

This form allows users to set project name, work order or purpose on creating a new project. Figure 3 shows the projects creation form.
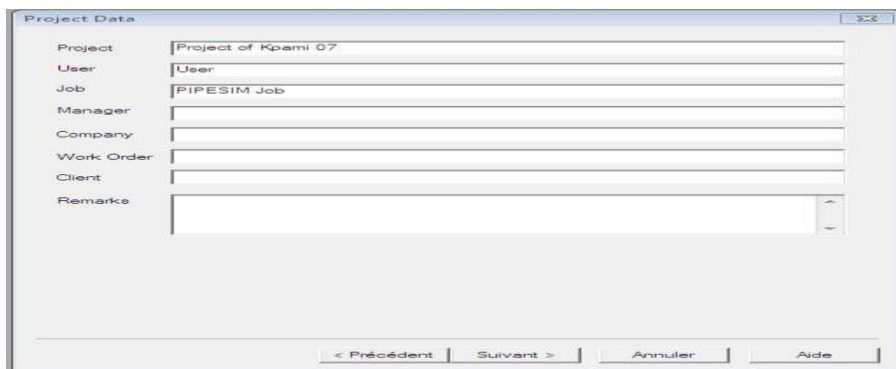

Figure3. *Project Creation Form*

2.2.2. Data Input Form

This form allows users to make selections and input data value for generating the different phase envelop for designing pipeline. Figure 4 shows the data input dialog. The < the set up/compositional > menu was used to enter the pure hydrocarbon components given for this study. All the pure hydrocarbon components were selected from the component database. Finally the < add> button was used to include all the pure hydrocarbon been selected.
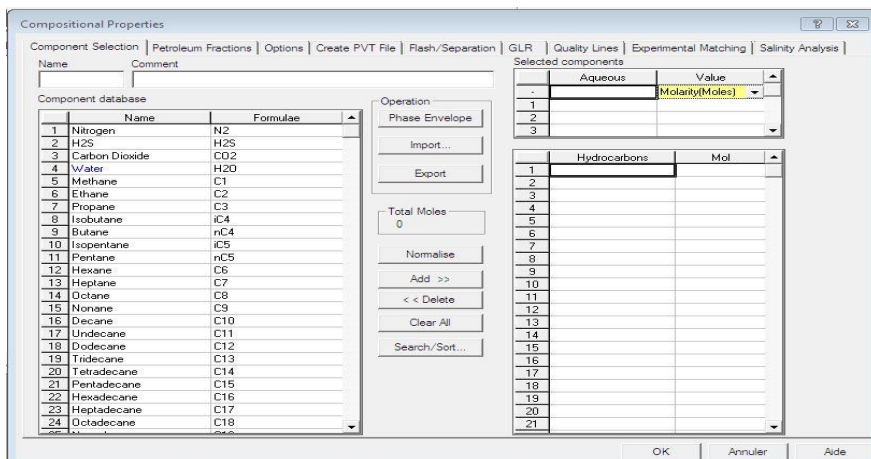
Figure4. *Data Input Form*

After the number of moles of pure components was added, the petroleum fraction tab was selected to characterise the petroleum fraction C7+ by entering the boiling point, the molecular weight and the specific gravity in row 1. The same procedure was repeated in order to enter the number of moles for C+ under the component selection tab. Also the hydrocarbon phase envelope was generated by selecting the phase envelop button, and its subsequent plot was obtained. Figure 5 show a hydrocarbon phase envelope plot.
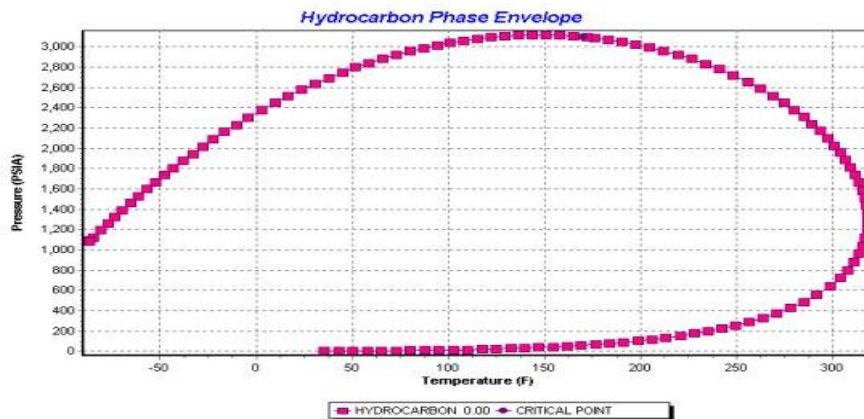
Figure5. *Sample of Plot of Hydrocarbon Phase Envelope*

2.2.3. Hydrate Phase Envelope Identification Process

It is necessary to add the aqueous component pure water. The < setup/compositional > menu was used to select water by pressing the add button of which its respective concentration value was then added. With the help of the phase envelop button, an aqueous phase envelope and hydrate formation line was generated. Figure 6 shows a sample of plot identifying the hydrate envelope.
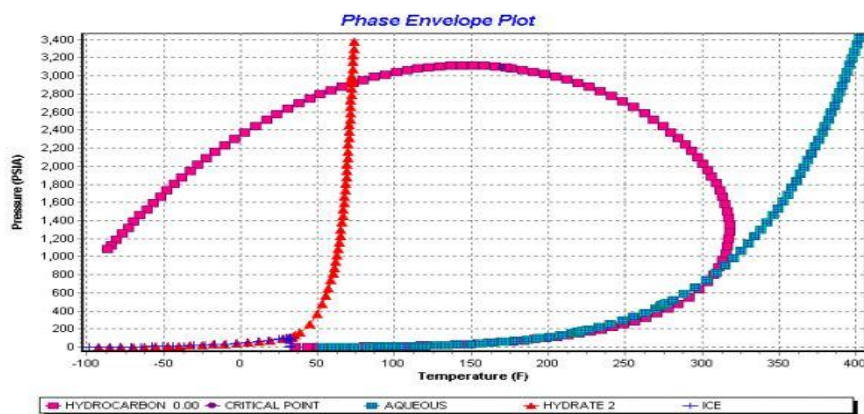
Figure6. *Sample of Hydrate Phase Envelope*

2.2.4. Pipeline Size Selection

The smallest pipeline ID that will allow the design flow rate of the gas to be transported from the satellite platform whilst maintaining an arrival pressure of not lower than that of the processing platform pressure is always the best. The tool bar allows the user to select all the necessary items as source, boundary nodes, risers and flowline for the completion of the model. Figure 7 show the tool bar.

Figure7. *Tool bar*

2.2.5. Design Form

This form displays the data and solution as one part also the pictograph of the designed prototype attached to a final report. An example of a completion model is shown in Figure 8.
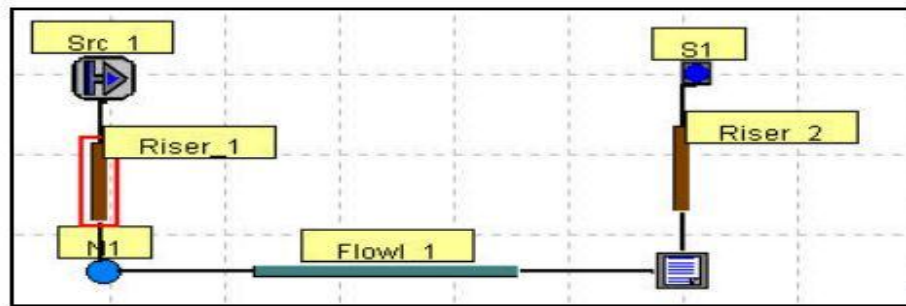
Figure8. *Completed Model Sample*

3. RESULTS AND DISCUSSION

An application software for designing subsea pipeline to transport gas from a satellite platform to a processing platform was developed that yielded a compositional analysis of the gas to be transported. However, the secondary data used for this study were obtained from Vioco Petroleum Limited, Côte d'Ivoire. Tables 1 to 8 present all the data used in this study.

Table1. *Boundary Conditions*

Fluid inlet pressure at satellite platform	1,200 psia
Fluid inlet temperature at satellite platform	176 °F
Design liquid flowrate	50 MMscf
Maximum turndown	28 MMscf
Minimum arrival pressure at processing platform	800 psia
Minimum arrival temperature at processing platform	73 °F.

Table2. *Pure Hydrocarbon Components*

Component	Moles
Methane	92.2300
Nitrogen	2.1411
Carbon (IV) oxide	0.5483
Ethane	2.8319
Propane	1.1232
i-Butane	0.2855
n-Butane	0.2984
i-Pentane	0.1319
n-Pentane	0.0938
n-Hexane	0.3159

Table3. *Petroleum Fraction*

Name	Boiling Point(°F)	Molecular Weight	Specific Gravity	Moles
C7+				

Table4. *Aqueous Component*

Component	Volume ratio (%bbl/bbl)
Water	10

Table5. *Pipeline Sizes Available*

I.D.(")	Wall thickness (")	Roughness (")
10	0.5	0.001
12	0.5	0.001
14	0.5	0.001

Table6. *Pipeline Data*

Height of undulations	10/1000
Horizontal distance	19 miles
Elevation difference	0
Wall thickness	0.5"
Roughness	0.001"
Ambient temperature	50 °F
Overall heat transfer coefficient	0.2 Btu/hr/ft2/°F

Table7. *Pipeline Insulation Study Data*

Pipe thermal conductivity	50 Btu/hr/ft/°F
Insulation thermal conductivity	0.15 Btu/hr/ft/°F
Insulation thickness available	0.75" or 1.0"
Ambient fluid	Water
Ambient fluid velocity	1.64 ft/sec
Burial depth	0 (half buried)
Ground conductivity	1.5 Btu/hr/ft/°F

Table8. *Data for Risers 1 and 2*

Horizontal distance	0
Elevation difference (Riser 1)	-30 m
Elevation difference (Riser 2)	+30 m
Inner diameter	10"
Wall thickness	0.5"
Roughness	0.001"
Ambient temperature	50 °F
Overall heat transfer coefficient	0.2 Btu/hr/ft^2/°F

3.1. Compositional Model of the Hydrocarbon Phase

A compositional fluid model allows the fluid physical properties to be estimated over the range of pressures and temperatures encountered by the fluid. The fluid model is made up of individual pure components such as methane, and petroleum fractions. Petroleum fractions are used to estimate the behaviour of groups of heavier pure components. The corresponding hydrocarbon phase envelope generated is shown in Figure 9.
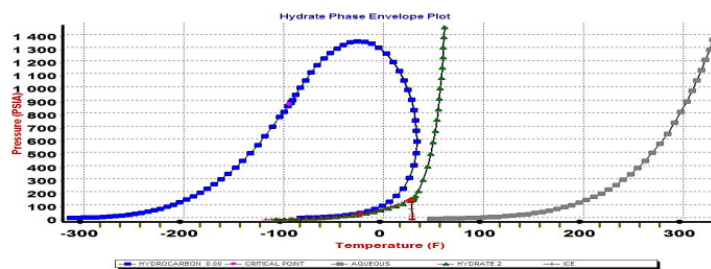
Figure9. *Hydrocarbon Phase Envelope Plot*

3.2. Identification of the Hydrate Envelope

Certain fluid composition shows the tendency to form hydrate compounds in the presence of water. These compounds can cause line blockages. Hydrate formation is also dependent on pressure and temperature. In this study, hydrate is to be avoided by operating above the hydrate formation temperature at all times. Figure 10 shows the plot identifying the hydrate envelope from the simulation after adding the aqueous component to the original composition.
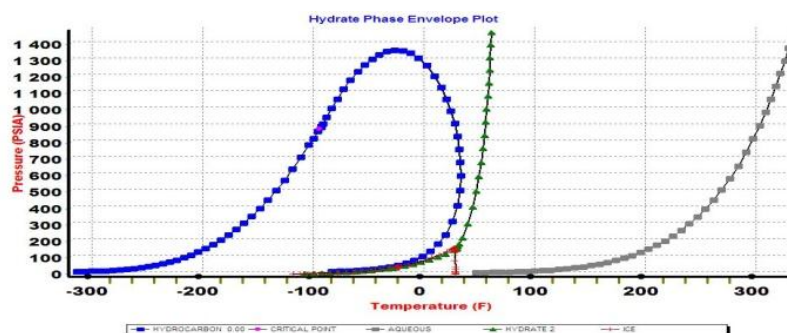
Figure10. *Hydrate Phase Envelope Plot*

From the hydrate phase envelope (Figure 10), it is noted that hydrates tend to form in the region on or to the left of the hydrate line. In this study, hydrate formation was simulated to occur at temperatures 65 °F and. It is advised to operate at temperatures above 65 °F at all times to avoided hydrate formation in the pipeline.

3.3. Pipeline Sizing

The size of the pipeline was determined by the computation of the production platform inlet pressure and temperature, the design flow rate, the roughness, the overall heat transfer coefficient and ambient temperature. Figure 11 represents the pipeline sizes available which are 10", 12" or 14"ID as described in the data section. Pipeline size 10" size the smallest pipeline size that will satisfy the arrival pressure condition of at least 800 psia (Figure 11).
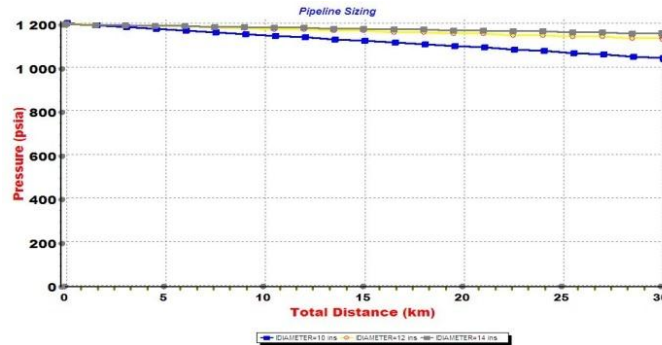

Figure11. *Pipeline Sizing*

3.4. Pipeline Insulation

The smallest thermal insulation thickness that can be used to insulate the pipeline and maintain an arrival temperature of not less than 73 °F was obtained. This minimum arrival temperature is required to prevent the formation of hydrates. The insulation had a thermal conductivity of 0.15 Btu/hr/ft/°F and a thickness of 0.75" or 1". First the pressure temperature profiles operation was used to simulate the temperature profile for the design and turndown flow rate cases with 0.75" thermal insulation thickness. Figure 12 shows the pressure temperature profile of the 10 in pipeline selected using a 0.75" thermal insulation thickness at design flow rate conditions of 50 MMSCF and maximum turndown condition of 20 MMSCF.
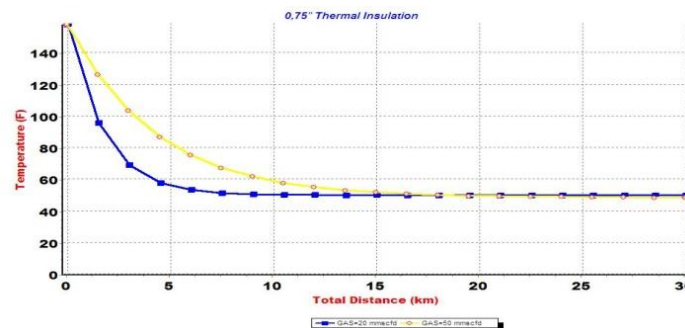
Figure12. *0.75" Thermal Insulation*

In Figure 13, the pressure temperature profiles operation was used to simulate the temperature profile for the design and turndown flow rate cases with 1"thermal insulation thickness. It can be indicated from Figure 13 that 1" insulation still cannot satisfy the requirement to maintain an arrival temperature of 73 °F.
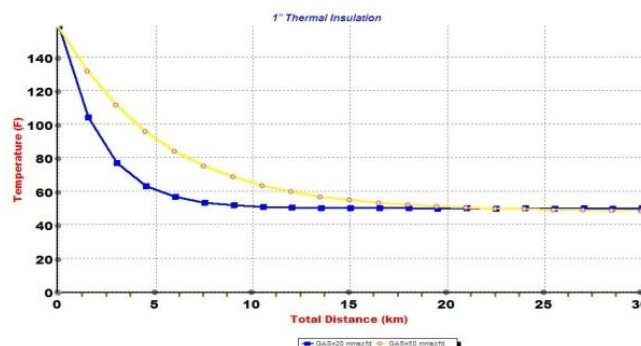

Figure13. *1" Thermal Insulation*

For an effective control of the hydrate formation, the system temperature was increased by combining insulation and heating process to meet the requirement of an arrival temperature of 73 °F. The ambient temperature was increased from 50 °F to 80 °F by direct electrical heating system as depicted in Figure 14.

Figure14. *0.75" Thermal Insulation Plus a DEH*

3.5. Design Form

Figure 15 is a general overview of the gas pipeline design comprising of riser 1 and riser 2 attached to the main flowline 1 of 10 in. The arrival point at satellite platform indicates SOURCE 1 whereas the boundary node S1 represent the arrival point at processing platform and then the other nodes N1 and N2 represent each end of the pipeline.
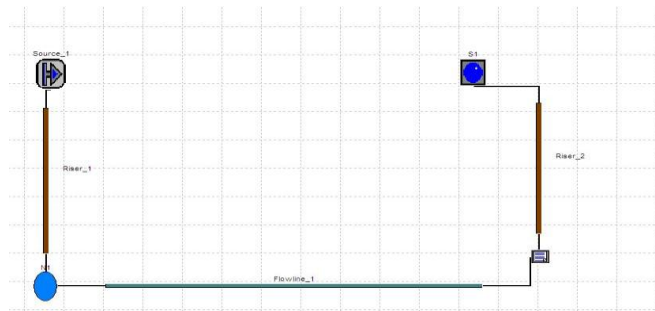
Figure15. *General View of the Designed Pipeline*

Hydrates are predicted to form at a temperature of 65 °F (Figure 10), hence the designed pipeline must be operated above this temperature at all times. The smallest and cost-effective pipeline size that will guaranty the transport of the gas along the desired distance of 30 km with consideration of arrival pressure of at least 800 psi is determined to be 10" (Figure 11), the other two pipeline sizes 12" and 14" ID simulated could be used to achieve the desired results but in other to optimise the design, 10" was selected for the design.

It is clearly estimated that 0.75" thermal insulation thickness (Figure 12), cannot be used to keep the system out of the hydrate region therefore the pipeline was thermally insulated with a 0.75" thermal insulation thickness and heated by the aid of Direct Electrical Heating (DEH) to maintain a steady state pipe temperature above the hydrate formation temperature as shown in Figure 14. The general view of the designed pipeline system with the source from the production platform, through riser 1 (-30 m), the flow line (30 km long) and up through riser 2 (+ 30 m) to the processing plant is shown in Figure 15. This confirms the impact of pipe insulation in practical design of gas pipelines.

4. CONCLUSION

The following conclusions can be drawn after a series of simulated work using PIPESIM software and data on Gazelle Field in Côte d'Ivoire:

- The conditions under which hydrate will form have been simulated and predicted to be 65 °F for the Gazelle Field.
- The composition of the product transported is of prime importance within the design process to prevent flow assurance challenges.
- Thermal insulation is a critical element in the design and operation of subsea pipelines, and in case of Gazelle Field, Direct Electrical Heating (DEH) was combined with insulation to avoid hydrate formation.

Nomenclature

Z = Compressibility factor for gas, dimensionless,

ρ = density, lbm/ft^3,

V = velocity, ft/sec,

g = gravitational constant, 32.2 ft/sec^2,

f = Moody friction factor, dimensionless,

L = pipe length, ft,

L_m = length, miles,

d = pipe diameter, ft,

ΔP = pressure drop, psi,

μ = viscosity, lbm/ft-sec.

SG = specific gravity of liquid relative to water (water = 1),

S = specific gravity of gas at standard conditions relative to air (molecular weight divided by 29),

Qg = gas-flow rate, MMscf/D,

Ql = liquid flow rate, B/D,

W = rate of flow, lbm/sec

$P1$ = upstream pressure, psia

$P2$ = downstream pressure, psia.

ΔhW = pressure loss, inches of water,

A = cross-sectional area of pipe, ft^2,

V_1 = specific volume of gas at upstream conditions, ft3/lbm,

P = operating pressure, psia,

R = gas/liquid ratio, ft3/bbl,

T = operating temperature, °R,

T_1 = temperature of gas at inlet, °R,

E = efficiency factor (new pipe: 1.0; good operating conditions: 0.95; average operating conditions: 0.85)

Assumptions

$$f = \left(\frac{1+3.6}{d} + 0.03d \right) \left(\frac{1}{1000} \right)$$

T = 520 °R,

P_1 = 15 psia,

Z = 1.0, and

ΔP = less than 10 % of P_1.

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AUTHORS' BIOGRAPHY

Solomon Adjei Marfo, is a Lecturer at the Petroleum Engineering Department of University of Mines and Technology, Tarkwa, Ghana. He holds PhD in Petroleum Engineering from the University of Port Harcourt, Nigeria, MEng Degree in Mining (Petroleum Engineering) from the University of Belgrade, Serbia and BSc in Chemical Engineering from the Kwame Nkrumah University of Science and Technology, KNUST, Kumasi, Ghana. He is a member of the Society of Petroleum Engineers (SPE), a Registered Environmental Specialist (RES) with the National Registry of Environmental Professionals (NREP) of USA. His research interests include sand and water control in oilfields using chemicals, agro-waste and local materials evaluation for oilfields application.

Prince Opoku Appau, is an MSc candidate at the Research Institute of Enhanced Oil Recovery of the China University of Petroleum (Beijing), majoring in Petroleum and Natural Gas Engineering. He holds BSc degree in Petroleum Engineering from the University of Mines and Technology (UMaT), Ghana. He is also a member of Society of Petroleum Engineers (SPE). His research interests include drilling fluids, rock petrophysics, reservoir engineering, EOR and natural gas engineering.