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Original Article

Design and Optimization of Glycol-Based Natural Gas Dehydration Plant

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Abstract *- Natural gas dehydration by Triethylene Glycol (TEG) is local content driven and highly imperative as it can reduce the water content of natural gas sufficiently in pipeline transmission and distribution standards. In the past, several research studies have proved that water vapour in natural gas causes the formation of hydrates, cakes, sludge, corrosion, and other flow issues. Hence, the design and optimization of glycol-based natural gas dehydration plants are important aspects of process engineering research. The TEG dehydration plant was designed using the advanced process simulation tool Aspen HYSYS to get different water content values in natural gas by varying the feed operating condition (temperature, pressure and flow rate) at a constant contactor pressure of 60 bar. The models relating the process feed conditions and the water content of sales gas were developed using Microsoft Excel (Solver), which was optimized using differential calculus to get optimum feed gas conditions of 22.32^{0}C and 89.08bar of temperature and pressure, respectively, with a water content of 0.0113kg H_2O/m^3 of Natural gas.*

Keywords *- Natural gas, Triethylene glycol, Petrochemical, Simulation, Aspen HYSYS.*

1. Introduction

Natural gas is an important source of energy used domestically and industrially. It is also a starting material for petrochemical production in the downstream [12, 13]. However, impurities or contaminants like water vapour that are associated with natural gas pose the threat of methane hydrate formation, cakes, blockages, corrosion, and other flow problems in gas processing plants and during pipeline transmission and distribution [1,11]. The natural gas industry has recommended the dehydration process to ensure that the water content of a dry gas is within the pipeline standard of not exceeding 0.112kg H_2O/m^3 of NG [6,14,16]. The dehydration process by TEG is considered the most successful and economical method of natural gas, and other methods are adsorption, condensation, and supersonic separation [9,17,18]. This research will therefore focus on the design and optimization of a glycol-based (TEG) natural gas dehydration plant using an advanced process simulation tool (HYSYS) as the design tool and Microsoft Excel (Solver) as the model developer and finally, differential calculus as the optimizer for determination of optimum feed gas condition (temperature, pressure and flow rate) for optimum and effective dehydration [19,20].

Several pieces of research have been done on TEG dehydration plants. Few of them are cited sequentially [5,21,22], stating that natural gas is a fossil fuel that is formed from the remains of plants and animals buried in the ground and in the presence of high or intense temperature and pressure [10,23,24] and that natural gas remains the third most widely used energy source in the world ranking just below coal [4,39,40]. According to [7,26], contaminants in a natural gas like water can cause corrosion and other flow problems during gas processing, transmission and distribution. According to the researcher, effective dehydration can be achieved by optimizing the flow rate of the Lean-TEG in the TEG dehydration plant using Microsoft Excel as the model developer and differential calculus as the solver to get the optimum Lean-TEG flow rate [27,28,29].

Anyadiegwu et al. [2] stated that though natural gas was once an unwanted by-product of crude oil production, presently, it provides over 20 per cent of all primary energy requirements in the world and, as such, has become an important factor in the development of countries as it provides energy for household use in our day-to-day activities, electricity, industrial and commercial. However, this natural gas contains certain impurities like water, which cause damage and corrosion during transmission through pipelines and distribution for use. They included that TEG dehydration is one of the best methods of removing the water associated with natural gas. This process or method of dehydration requires a good knowledge of natural gas properties like gas-specific gravity, pseudocritical pressure, temperature, viscosity, compressibility factor, gas density and gas compressibility to design and analyze natural gas production and processing systems. They designed and simulated a natural gas dehydration plant using HYSYS to obtain a clean, dry, wholly gaseous fuel.

Kinigoma & Ani [8] Comparison of Gas Dehydration Methods based on Energy Consumption. The researchers compared the three conventional methods of natural gas dehydration, absorption, adsorption, and condensation by developing energy balance models/equations for the three dehydration methods. They considered a natural gas with a given water content, temperature range as well as changes or variations in pressure and arrived at the following conclusion: There is a decrease in energy consumption as the pressure increases in the process; at high pressure, the condensation method of dehydration requires the least amount of energy, at high pressure and low temperature, TEG dehydration (absorption method) is more suitable and finally, at low dew point temperature, solid desiccant adsorption is more preferable.

Arubi et al. [3] optimized a glycol dehydration system for maximum efficiency—a case study of a gas plant in Nigeria. The researchers described natural gas as one of the cleanest, safest, most useful energy sources and a vital component of the world's energy supply. They also identified impurities like water vapour as one problem associated with natural gas because of its capability to cause great problems in the oil and gas industry. They emphasized that absorption by TEG has been the most popularly used method of natural gas dehydration for decades because of its ability to reduce the water content of natural gas to less than 0.112kg H_2O/m^3s of NG [6], which is a very low natural gas dew points as required for gas transmission pipelines. They stated that natural gas dehydration is important. Its objectives include Meeting the water dew point requirement for sales gas that is stipulated for buyers or users, Preventing hydrate formation in downstream units with low operating temperatures, Preventing pipeline corrosion since process gas may be contaminated by acid gases (CO_2/H_2S), Minimizing free water condensing in the pipeline thereby reducing the internal cross-sectional area of the pipe available for flow and causing partial blockage and consequential reduce the flow of gas.

The design and optimization of glycol-based natural gas dehydration plants are crucial aspects of gas processing industries [36,37,38]. The proper functioning of these plants holds significant importance in producing, transporting, and distributing natural gas by eliminating water vapour from natural gas streams [9,30,31]. This study highlights the key parameters that influence the efficiency of glycol dehydration plants and shows the impact of temperature, pressure, glycol concentration, and gas flow rates on the dehydration process. Furthermore, optimization through modelling, simulation, and design considerations enhanced the plant's overall performance, making it energy-efficient and cost-effective [32,33]. A well-designed and optimized glycol-based natural gas dehydration plant can help to meet quality standards, reduce operational costs, and improve the profitability of gas processing industries [34,35].

2. Materials and Method

2.1. Materials

The materials needed in this research are the feed material, temperature, pressure, and flow rate of the characterized natural gas, which is composed of Methane, Ethane, Propane, i-butane, n-butane, i-pentane, n-pentane, Hydrogen sulphide, carbon dioxide, nitrogen, water, and TEG as an absorbent used in the dehydration process. Dehydration plant with the following units: Inlet cooler, Inlet scrubber, contactor/absorber column, flash valve, flash separator, filters, heat exchanger, regenerator/distillation column, stripping column and circulation pump.

2.2. Method

Design and simulate the TEG natural gas dehydration plant using Aspen HYSYS and data in Table 1. Optimization of the TEG dehydration plant (Figure 1), using Microsoft Excel (Solver) and differential calculus (optimizer) as the optimization tools to determine the optimum feed gas condition (temperature, pressure and flow rate) for optimum performance of the plant at constant contactor pressure.

2.2.1. Natural Gas Composition and HYSYS Simulation Operating Condition

Table 1. Natural Gas Properties

Components	Composition	Molar Mass (g/mol)
C_1	0.8939	16.00
C_2	0.0310	30.00
C_3	0.0148	44.10
i-C_4	0.0059	58.12
n-C_4	0.0030	58.12
n-C_5	0.0005	72.15
i-C_5	0.0010	72.15
H_2O	0.0050	18.00
N_2	0.0010	14.00
H_2S	0.0155	34.10
CO_2	0.0284	44.00
TEG	0.0000	150.154
Total	1.0000	610.894
Operating Condition		
Pressure(kPa)	6205.2832	
Temperature (^{0}C)	29.4444	
Flow rate (kg/s)	768.6343	

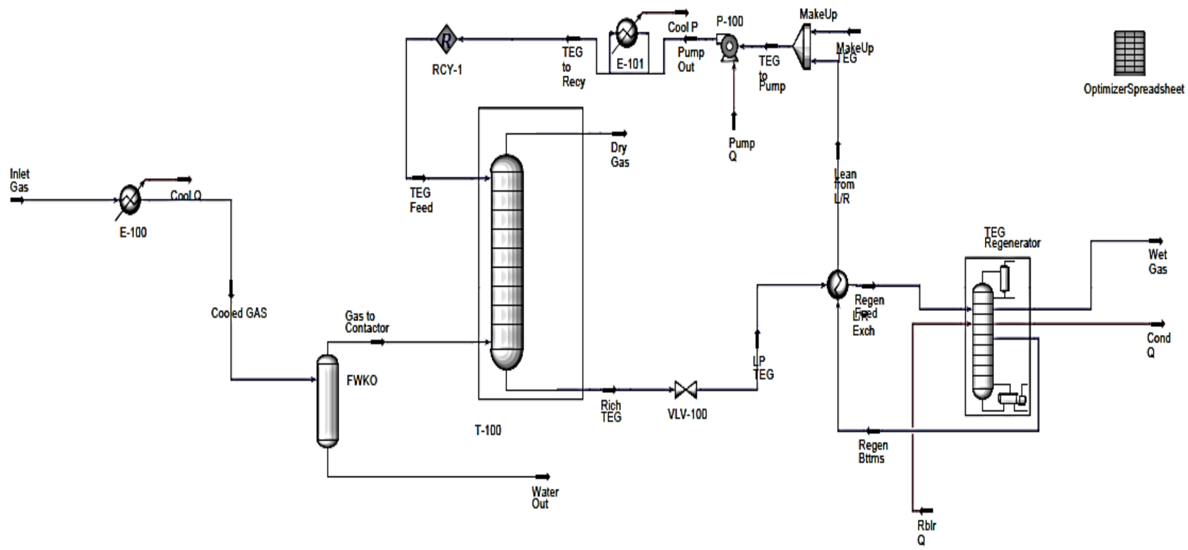

Fig. 1 Process flow diagram of natural gas dehydration unit

2.2.2. Description of the Parameters that are considered in the process Optimization, Procedures for Data Collection and their Significance

In this research, an aspen HYSYS case study of a TEG package and natural gas will be developed and simulate the characterized natural gas process condition. To achieve the primary aim of the research, which is to optimize the design of the TEG plant configuration regarding the water content of dry Natural Gas (NG) using the dependent parameters (output variables) and the independent parameters (input variables).

Dependent Parameters

These are also called performance parameters, and they are variables that depend on the other system parameters (independent variables). These variables determine the performance and efficiency of the system. They are obtained from HYSYS flash calculation.

Independent Parameters

They are also called system parameters and are used to describe the characteristics or properties of the flow system and the system control mechanism. They do not depend on other variables in the simulation and can be directly manipulated by the researcher during the simulation process.

The procedures for generating data of the three major dependent process functional parameters (temperature, pressure, and flow rate) will be described extensively:

Natural Gas Feed Temperature

This refers to the temperature of the natural gas at the inlet to the contactor/absorption column immediately after the scrubber. During the case study analysis, the natural gas feed temperature varied from 40C to 400C at an interval of 40C using the HYSYS simulation software at a constant feed pressure, flow rate, and contactor pressure of 60 bar in the plant design with the best performance characteristics. The water content of the natural gas will be flash-calculated and recorded at various feed temperature conditions. The data collected above will be transported to an Excel spreadsheet where the graph of sales of natural gas water content versus natural gas feed temperature gas will be plotted for plant design with the best performance characteristics at a contactor pressure of 60 bar. This plot will show the relationship between the change in natural gas feed temperature and the water content of sales gas.

Natural Gas Feed Pressure

This also refers to the natural gas pressure at the inlet to the contactor/absorber through the scrubber. During the case study analysis, the natural gas feed pressure is varied from 30 bar to 120 bar at an interval of 10 bar using the HYSYS case study platform at constant feed temperature, flow rate, and average contactor pressure of 60 bar in the plant design with the best performance characteristics. The corresponding water content of sales gas will be flash-calculated and recorded at various feed flow rate conditions.

The data collected above will also transported to an Excel spreadsheet, which shows the plot or relationship between the water content of sales gas against natural gas feed pressure for the plant with the best performance characteristics at a constant pressure of 60 bar.

Natural Gas Feed Flow Rate

This refers to the natural gas flow rate at the inlet of the contactor or absorber through the scrubber. During this case study analysis, they varied it from 550kg/S to 1000kg/S at an interval of 50kg/S using HYSYS simulation software at constant feed temperature, pressure and contactor pressure of

60 bar in the design with the best performance characteristics. The corresponding water content of sales gas will be flash-calculated and recorded.

The data collected above will be transported to an Excel spreadsheet where a plot of the relationship between the natural feed flow rate and the water content of sales gas will be shown.

2.2.3. Development of Optimization Models

This process involves the use of optimization tools such as the solver (Excel spreadsheet) and optimizer (differential calculus)

The Solver

This refers to a platform or system that can generate a mathematical or theoretical model of the relationship between the performance and system parameters or variables under investigation in the optimization process. This mathematical model could be linear, quadratic, polynomial, exponential, logarithmic, etc. A good solver should also give an idea of the degree of accuracy in fitting the data from which the mathematical model is developed. In this research, an advanced process engineering software called Excel spreadsheet will be used as the solver because of its ability to demonstrate a high degree of accuracy and precision in generating graphical and mathematical models from data of relation between variables of parameters.

Optimizer

This is a tool or platform that generates the optimization conditions of the mathematical models depending on the condition and behaviour of the model and the system from which the model is developed. Differential calculus will be deployed as the optimizer in this research as a result of its ability to determine the maximum, minimum and reflex point conditions of mathematical models, especially the polynomials [15]. Below are differential calculus optimization conditions for different degrees of polynomial functions

Linear Models

This refers to the model or equation in which the highest power of the independent variable (x) is one. Generally given mathematically as:

$$y = mx + c \tag{1}$$

Where,

y = Dependent variables like water content of the dry gas at the exit of the contactor (WC), optimum temperature (T_o), optimum pressure (P_o), and optimum flow rate (F_o), etc.

x = Independent variables like feed inlet temperature, feed inlet pressure, feed inlet flow rate, average contactor, pressure, etc.

At the optimum point,

$$\frac{dy}{dx} = Constant \tag{2}$$

In this case, optimization condition cannot be determined from the model; therefore, other process conditions like economics (minimizing cost, for instance, by replacing an energy-consuming equipment (cooler) with a non-energy consuming equipment (heat exchanger), proper feasibility study, material choice, and safety consideration will be considered as criteria for optimization.

Quadratic Models

This is a model in which the highest power of the independent variables is two. They are mathematically stated as:

$$y = A\mathrm{x}^2 + \mathrm{Bx} + \mathrm{C} \tag{3}$$

Where x is the independent variables (input data), and y is the dependent variable (output results), A & B are coefficients of input data, and C is a constant value.

At the optimum point,

$$\frac{dy}{dx} = 0 \tag{4}$$

$$\therefore \frac{dy}{dx} = 2Ax + B = 0 \tag{5}$$

$$x = \frac{-B}{2A} \tag{6}$$

In this case, the optimum condition could be maximum or minimum depending on the sign of the coefficient of x^2. When the coefficient of x^2 is positive, the value of x at the point of $dy/dx = 0$ gives a minimum value for y, but when the coefficient of x^2 is negative, the value of x at the point of $dy/dx = 0$ gives a maximum value of y.

Polynomial Models

These are models in which the highest point of the independent variables x is three and above. They are mathematically given as follows:

$$y = Ax^n + Bx^{n-1} + Cx + D \tag{7}$$

Where n = 3, 4, 5, …

Considering when n is 3

$$y = Ax^3 + Bx^2 + Cx + D \tag{8}$$

At the optimum point, $\frac{dy}{dx} = 0$

$$\therefore \frac{dy}{dx} = 3Ax^2 + 2Bx + C = 0 \tag{9}$$

Note that this is a quadratic model, which implies that x will have two values that will satisfy the condition above. Hence, we will have two optimum values of y, one minimum and one maximum. If the coefficient of x^3 is positive, the minimum comes before the maximum, but if it is negative, the maximum will come before the minimum.

For higher-degree polynomial models like

$$y = Ax^4 + Bx^3 + Cx^2 + Dx + E \quad (10)$$

At the optimum point, $dy/dx = 0$

$$\frac{dy}{dx} = Ax^3 + 3Bx^2 + 2Cx + D = 0 \quad (11)$$

Note that this is a polynomial of degree three, meaning that there are three values of x that satisfy the condition above. Hence, we will have three optimum conditions: one minimum, two maximum or one maximum, and two minimum. If the coefficient of x^4 is positive, we will have the first minimum, second maximum and third minimum. But if it is negative, we should expect the first minimum, second minimum and third maximum.

Finally, for high-degree polynomials, it may be reasonable to model such cases as Sinusoidal cases for simpler analysis. However, it is advisable to model system variables based on polynomial functions for easier and straightforward analysis.

2.2.4. Optimum Water Content Determination at Optimum Temperature and Pressure Feed Gas Condition

$$WC = 593335e^{(0.005486\,T_G)}.\ P_G^{\ -0.81462}$$

(Netusil & Ditl [6]) (12)

Where,
WC = Optimum water content in kg of water per $10^6 m^3$ of NG
T_G = Optimum feed temperature in ^0C
P_G = Optimum feed gas pressure in mpa

The objective and constraint function of the optimization process are stated as follows;

$$\text{Minimize WC} = F(T, P, F) \quad (13)$$

$$\text{Subject to } 0 \leq T \leq 40 \quad (14)$$

$$0 \leq P \leq 120 \quad (15)$$

$$0 \leq F \leq 1000 \quad (16)$$

Where WC is the water content in (Kg H_2O/m^3 of NG) T is the feed temperature in (K), P is the feed pressure in (Bar), and F is the flow rate of the feed in (Kg/S). The models were solved using a combination of Microsoft Excel and differential calculus as the optimization tools.

3. Results and Discussion

The optimization results of the natural gas feed condition (temperature, pressure and flow rate) at a constant contactor pressure and their corresponding water content of sales gas in the TEG dehydration plant process are presented in figures 2, 3 and 4 below.

3.1. Optimization of Natural Gas Feed Temperature at Contactor Pressure of 60bar

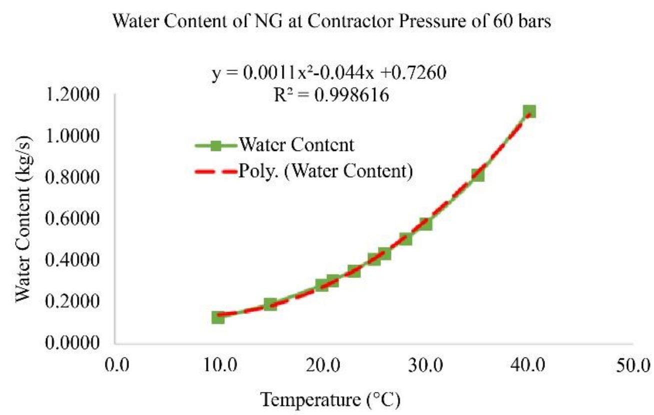

Fig. 2 Plot of Water Content of Sales Gas against Feed Gas Temperature at Contactor Pressure of 60bar

Figure 2 shows the mathematical model and variation of the water content of sales gas and the feed gas temperature of the TEG dehydration plant design configuration at a contactor pressure of 60 bar. Here, it is observed that the variation of the water content of sales gas increases as the feed gas temperature increases (GSPSA)[7]. The mathematical model relating the natural gas feed temperature and water content of sales is given as follows:

$$y = 0.0011x^2 - 0.044x + 0.7260 \quad (13)$$

Where y is the water content of sales gas (WC), and x is the feed gas temperature (T). Therefore, equation (13) transforms to

$$WC = 0.0011T^2 - 0.044T + 0.7260 \quad (14)$$

Differentiating equation (14) with respect to T gives rise to a linear model that can be solved at the stationary point as follows.

$$\frac{dW}{dT} = 0.0022T - 0.04471 \quad (15)$$

At the stationary point, equation (15) transforms to

$$0.0022T - 0.04471 = 0 \quad (16)$$

$$T = \frac{0.04471}{0.0022}$$

$$T = 20.32^0C$$

The optimum temperature T = 20.32^0C can be substituted into equation (14) to give a water content WC = 0.287kg/S.

The value of $R^2 = 0.998616$ shows the level of accuracy of the optimization model when compared with the HYSYS optimization simulation result on a scale of 0 to 1.

3.2. Optimization of the Natural Gas Feed Pressure at Contactor Pressure of 60bar

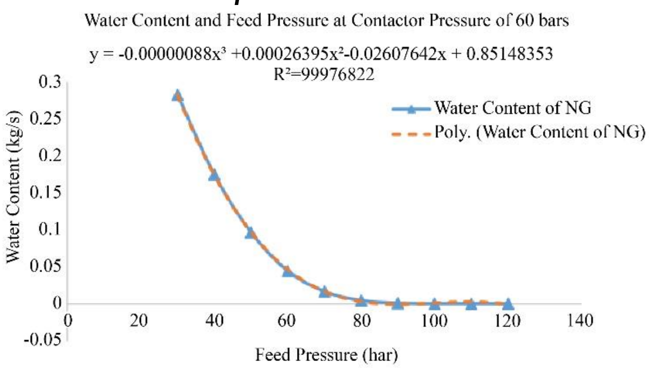

Fig. 3 Plot of Water Content of Sales Gas against Feed Gas Pressure at Contactor Pressure of 60bar

Figure 3 shows the mathematical model and variation of the water content of sales gas and feed gas pressure of the changed plant design configuration at a contactor pressure of 60 bar. Here, the variation of the water content of sales gas and feed gas pressure is inverse exponential. The mathematical model relating the natural gas feed pressure and water content of sales gas is given as follows:

$$y = -0.00000088x^3 + 0.00026395x^3 - 0.02607642x + 0.85148353 \quad (17)$$

Where y is the water content of sales gas (WC), and x is the feed gas pressure (P). Therefore, equation (17) transforms to

$$\text{WC} = -0.00000088P^3 + 0.00026395P^3 - 0.02607642P + 0.85148353 \quad (18)$$

Differentiating the polynomial model gives rise to a quadratic model as follows:

$$\frac{dWC}{dt} = -0.000000264P^2 + 0.0005279P - 0.02607642 \quad (19)$$

Equation (19) can be solved at a stationary point using the quadratic formula

$$P = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad (20)$$

Where a = -0.00000264, b = 0.0005279 and c = -0.02607642

Substituting a, b and c values into equation (18) gives minimum and maximum pressure values of 89.08 bar and 110.88 bar with corresponding water content of 0.00106kg/S and 0.00561kg/S using equation (18). Here, the optimum feed gas pressure is the pressure value with the least water content (GSPSA) [7]

3.3. Optimization of the Natural Gas Feed Flow Rate at Contactor Pressure of 60bar

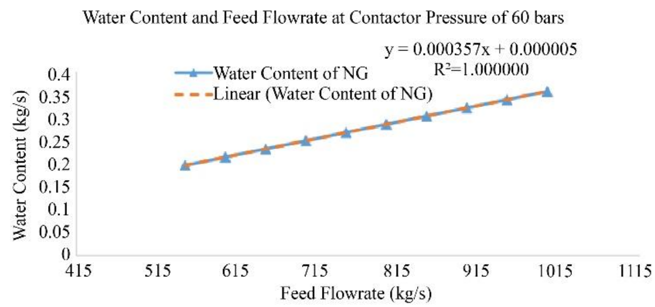

Fig. 4 Plot of Water Content of Sales Gas against Feed Flow Rate at Contactor Pressure of 60 bar

Figure 4 shows the linear mathematical model and variation of the water content of sales gas and feed gas flow rate of the modified plant design configuration at a contactor pressure of 60 bar. Here, the water content relationship with the sales gas is linear and increases directly proportional to the feed gas flow rate. The mathematical model relating the natural gas feed flow rate and water content of sales gas is given as

$$y = -0000357x + 0.000005 \quad (21)$$

Where y is the water content (WC), and x is the feed gas flow rate (F)

Therefore, equation (21) transforms to

$$\text{WC} = 0.000357\text{F} + 0.000005 \quad (22)$$

Equation (22) shows that optimization conditions cannot be determined from this model, but other conditions like safety, economics, control, etc. can be considered. This model is valid considering the water content determination equation given by Netusil & Ditl [9]

$$WC = 593335e^{(0.005486\,T_G)}.\ P_G{}^{-0.81462} \quad (23)$$

According to Netusil & Ditl [9], the optimum water content of sales gas is a function of feed gas temperature and pressure.

4. Conclusion

To mitigate the problem facing process industries during natural gas processing, storage, distribution, and transmission in pipelines as a result of water associated with it, the TEG dehydration process is recommended for effective and efficient dehydration. In this paper, process simulation software Aspen HYSYS was integrated as the TEG dehydration plant design tool.

For optimum performance of the dehydration plant, optimization tools such as Excel Spread Sheet (Solver) and Differential Calculus (Optimizer) were integrated to obtain the optimum feed gas conditions of 22.32^{0}C and 89.08bar of temperature and pressure, respectively, with corresponding water content of 0.0113kg H_2O/m^3s of NG, which is within the limit of water content specification for pipeline transmission.

Declarations

Authors' Contributions

WCO, EME conceptualization, methodology, original draft preparation, performed experimental work, and writing.

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