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Proportional, Integral and Derivative Control Strategy of Triethylene Glycol Recovery Regenerator for Optimum Natural Gas Dehydration Process

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Abstract The research considered the application of the conservation principle of mass and energy balance in the development of the dynamic model of a triethylene glycol (TEG) recovery regenerator. The mass and energy balance was performed at the feed point (inlet) and the bottom (outlet) of the regenerator. The natural gas TEG dehydration plant was designed using HYSYS while the control analysis was performed at the feed point and bottom (reboiler) of the regenerator. The behaviour of the process was analyzed in terms of an open loop with disturbance and a closed loop for both manual and automated proportional, integral and derivative (PID) control configurations using Simulink. The effect of the process variable (temperature) was measured using a thermocouple configured in the closed-loop system. The result of process behaviour for an open loop system with a disturbance at the feed point, and reboiler section as a function of temperature with time indicates a high level of process instability. While the use of manual tuning of various PID controllers. Parameters or gains in the closed loop system for temperature control at the feed point and reboiler section of the regenerator also showed a high degree of system or process instability as indicated in the temperature and time profile behaviour, where the system failed to attain its stability even at 10seconds. However, the use of automated controller gains of (1.438,-2.733, and 0.1864) and (0.1773, 0.1665, and 0.04408) for $K_P, K_I \text{ and } K_D$ at the feed point and reboiler section of the regenerator showed that the system attained its stability at 10seconds and 2.5seconds after a tuning of 402.5 times and 205.3 times respectively and at a set point temperature of 80°c for the regenerator feed point and 204^{0}C for the regenerator reboiler section. The above analysis clearly shows that for optimum TEG recovery during the dehydration process, the use of an automated PID controller gives a better performance characteristic compared to manual tuning and ensures the system or process attains its stability within the shortest possible time.

Keywords: Natural gas, Triethylene glycol, PID Control Strategy, Simulation, Aspen HYSYS

I. Introduction

One important technique of ensuring effective and efficient dehydration of natural gas to meet the standard required by process industries for gas pipeline transmission is optimum triethylene glycol (TEG) recovery in the regenerator or distillation unit during the absorption process in a TEG dehydration plant [1]. To enhance TEG recovery process variables such as temperature and pressure must be controlled using the conventional proportional integral derivative (PID) controllers [2; 3]. The control of temperature is very necessary and vital because of it variation in the regenerator due to the presence of a condenser and reboiler and the top and bottom of the regenerator [4; 5]. Research in the past and recent past has shown the importance of process control of the distillation column, its design, and the role it plays with the absorber unit in a TEG dehydration plant [4; 7].

[8; 9] researched on design and performance

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analysis of an industrial TEG recovery generator of a dehydration process and stated that natural gas is a major source of energy utilized in the world but certain impurities such as water vapour, carbon dioxide, and hydrogen sulfide that comes along with it during its formation in the reservoir must be sufficiently removed. The water content associated with the gas results in the formation of hydrates which cause corrosion to processing facilities or during transmission of the gas and must be removed to meet the water in gas amount of about 0.112kg H_2O/m^3S of dry gas as recommended by the process industries for gas transmission via pipeline [10; 11]. The water content of gas can be removed using different methods but the most generally used technique is absorption by TEG in a dehydration system [12; 13; 14; 15]. The natural gas TEG dehydration system is made up of several units or equipment but can be divided into absorption and regeneration units. The absorption unit is where the water content of the gas is absorbed by TEG while the research unit is where the mixture of TEG and water (rich TEG) is separated using the principle of distillation (difference in boiling point or volatility) [16; 17]. The researchers noted that certain factors such as TEG composition, regeneration temperature, pressure and stripping gas flow rate affect the performance of the TEG recovery regenerator system during operation [18]. The performance of the regenerator is greatly influenced by the flow rate of the stripping gas [19; 20]. The reboiler configured in the regenerator plays an important role in the temperature stability of the process for optimum TEG recovery [21; 22]. The mass and energy balance principles can be applied in the development of design sizing models of the TEG recovery column for determination of the column's height, diameter, area, and volume as well as investigation of the column's performance through analysis of the flow and overflow of mass and energy streams from the HYSYS simulation of the plant which demonstrates the impact of regenerator in the effective and optimum natural gas absorption process [23; 24; 25].

[23] researched on economic comparative analysis of the use of dry natural gas and nitrogen gas for stripping during rich TEG separation in a regenerator of the TEG dehydration process and stated that the natural gas dehydration process helps in preventing problems like corrosion, blockages and water condensation during pipeline transportation [26; 27; 28]. They performed an economic analysis on the use of dried natural gas obtained from the absorption process as the stripping gas in rich TEG separation and the use of nitrogen gas for the same purpose by investigating the results of mass and energy balance streams obtained from the HYSYS simulation of the process.

[29] designed a natural gas dehydration tower and described natural gas as a catalyst for economic development in the world [8]. It is the most convenient, economical, efficient, and cleanest source of energy compared to crude oil and other energy sources and acknowledged the negative impact of certain contaminants or impurities such as water, carbon dioxide, and hydrogen sulfide associated with natural gas which causes problems like corrosion, blockage of pipeline, spray nozzles and separation equipment during processing [30; 31]. They stated that TEG dehydration is the most economical method of natural dehydration where the TEG serves as an absorbent capable of absorbing the water content of the gas to form a rich-TEG (TEG plus water mixture) which is later separated in the TEG

regeneration unit to form a lean TEG that is recycled for further absorption process [32; 33].

[3] performed a comparative analysis of absorption, adsorption and condensation methods of gas dehydration based on energy efficiency or consumption and developed the energy balance models of the dehydration methods using natural gas with specified water content, temperature range and differential pressure. The profile of the simulated models shows that an increase in pressure results in a decrease in energy loss of the process which favours the condensation method of dehydration, at high pressure and low temperature, TEG dehydration (absorption method) is suitable and efficient. Finally, at low dew point temperatures, solid desiccant absorption is preferable [20].

[34], researched modelling and control of distillation as the commonly used method of separation in the petroleum industries for final product purification. The components of the distillation column help in enhancing both mass and energy transfer during the process while trays or plates help in more product separation. It is configured with a reboiler at the bottom of the column which supplies heat to the system and a condenser at the column top for cooling and condensing of vapours [35]. The researchers focused on the development of mass and energy balance models of the distillation column with 130,000tons capacity of raw condensate per year based on 24 operating hours per day and 350 working days per year with product purity of not less than 98%. The non-linear terms of the complex process were linearized using Taylor's series expansion techniques and simulated to help provide the initial steps of a petroleum project feasibility study and design. The reduced-order linear model is utilized as a base model for an MRAC controller. The controllers (MRAC and PID) theoretically provide a platform for plant output tracking the reference set points and ensure product quality regardless of the disturbances or load encountered during operation [36]. The research failed to consider experimental production factors, specifically designed structures, parameters estimation and validation of the system and was only based on physical laws and so proved that the MRAC controller is not suitable for the online handling of the process constants.

[33] stated that distillation is one of the most frequently used methods of separation in process industries that are capable of separating the components of a mixture based on their volatility or difference in boiling points and on the difference in the compositions of the liquids and their vapours. The product purity of a distillation process is maintained by manipulating the material and energy balance of the process [37; 29].

However, certain factors such as dead time, non-linearity and variable interactions, make it difficult to maintain the purity products. The process of distillation can be performed either as a batch or continuous operation. The main difference between the two is that in continuous distillation, the feed concentration is relatively constant while in batch, the concentration of the less dense components drops and that of the heavy components rises as the distillation progresses. Another basic difference between distillation operations is in the handling of the best removed by the condenser at the column top [38]. The more common approach or technique is to waste that heat by rejecting it into the cooling water.

In this case, pay heat must be used at the bottom of the column in the reboiler. A large part of the total operating cost is dependent on the provision of heat required at the reboiler. In some distillation systems, the heat content of the bottom product is used to preheat the feed to the column [39].

[40] stated that in the chemical engineering field, the main unit operation for liquids and vapour separation and purification is the distillation unit. This unit is capable of separating a feed of a mixture of chemicals or liquids substances into the less dense or more volatile components in the distillate or overhead stream at the column top and the more dense or less volatile components at the column bottom (bottom stream). For effective distillation, the column is configured with automated value to a controller output signal for manipulating input and output flow rates (manipulating variables).when considering a continuous binary mixture separation, the input streams are the feed, boil-up and reflux while the output streams are the product of the distillate, bottom and small vent stream of inerts or light vapours exiting the reflux drum [23; 19]. Process variables such as flow rate, pressure and temperature signal from a sensor and transmitter are the inputs to the controller that must be controlled to a set point or desired value. Other variables to be controlled in a distillation column are column pressure, the liquid level of the reflex drum, the liquid level of the column bottom, the separation power base, and the material balance split. Control strategies such as cascade, feed-forward ratios, model-based computer control and conventional feedback control techniques can be used to control the process variables [9]. For instance, one common strategy for controlling the column pressure is to manipulate the value in a vent line from the reflux drum. Also, another line and automated value can be configured to inject inerts like nitrogen before the vent value. For the vapour stream exiting at the distillate, the condenser may need to run as a partial condenser with temperature-controlled cooling liquid on the condenser. For temperature control with distillate flow rate, a column temperature controller is used to manipulate the controller value in the distillate line. Also, the reflex drum level controller helps in manipulating a value in the reflex line and the column base level controller manipulates a value in the bottom line [41].

[33] also researched on computational simulation study for a techno-economic comparison of conventional and stripping gas methods for optimum TEG recovery during dehydration. According to the researchers, natural gas is one of the crucial and safest energy sources utilized industrially and domestically [42]. It is ranked 24% of the global energy consumption [43]. They described the water content of natural gas as a major setback in process industries because of the hazards it poses ranging from hydrate formation to pipeline corrosion and blockages. These problems can be controlled or mitigated using the TEG absorption method of dehydration. The researchers focused on the regeneration unit where TEG regeneration of separation of rich TEG mixture takes place. They performed a comparative analysis between the conventional dehydration method (com) and the stripping gas method (SGM) using HYSYS as the simulation tool to determine the most cost-effective method of TEG recovery by optimizing the operating parameters of both processes using sensitivity analysis which proved that the stripping gas method (SGM) is more economically and technically feasible.

In this research, process control analysis was considered in the regenerator/distillation unit as a result of the large or significant temperature difference between the top and the bottom of the column due to the presence of the condenser and the reboiler in the unit. The control of processes is highly imperative in process industries based on its application in the modification of system behaviour to a specific desirable manner over time, the ability to enhance productivity or optimum yield by ensuring best practices during operation, reduction of human or system errors thereby minimizing the cost of operations and production as well as predicting the behaviour of a system or process and determination of its stability.

Process control also helps to indicate how fast and smooth the error between the output and set point is driven to zero and the performance level of the control system in handling unexpected disturbances, sensor noise, and internal dynamic and steady-state changes during a process.

In the regenerator, the controller model development will be considered at the feed point and bottom (reboiler) of the regenerator to account for the temperature effect or variation during the TEG recovery process. This aspect of the research requires good knowledge and experience of the application of mass and energy balance principles in process dynamic model development, application of Taylor's series for non-linear model linearization, Laplace transform and the use of matrix in solving simultaneous models.

II. Materials and Methods

The materials used in this research are computer set, data obtained from the characterized natural gas and its operating condition as well as the process simulation tools such as HYSYS, and Simulink. The research methodology is both quantitative and qualitative

A. HYSYS Simulation of the Natural Gas TEG Dehydration Plant

The natural gas dehydration process by TEG technologically as shown from the HYSIS simulation process flow diagram in Figure 1 is made up of several units of equipment that make up the dehydration plant. But this plant can divided into the subscription unit where the natural gas absorption takes place and the regenerator unit where the lean TEG regeneration takes place. The plant consists of an inlet cooler through which the raw natural gas passes to maintain its temperature for effective absorption. The cooled natural gas from the cooler passes through a separator where partial dehydration and removal of certain impurities take place before it is sent to the contactor column where the gas absorption by TEG takes place. Here, the wet gas enters through the bottom of the contactor while the TEG is fed through the top section of the contactor. In the column, the lean TEG absorbs the water to form a rich TEG (mixture of TEG and water) which is exited through the bottom of the column while the dry gas exits through the column top. The rich TEG passes through a control value to ensure flow control before it is sent to the best exchanger for regulation for effective distillation in the regenerator column. In this column, the rich TEG mixture is separated using the principle of difference in volatility or boiling point between water and TEG. The water exits the column at the column top while the TEG which is less volatile exits through the column bottom and is recycled for continuous absorption. The recycled TEG is passed through a heat exchanger to a mixer where a make-up TEG is introduced to improve the virginity of the lean TEG. The lean TEG passes through a pump for flow regulation before it enters the heat exchanger unit for temperature regulation to meet the specified temperature range of lean TEG to be used for further absorption in the plant.

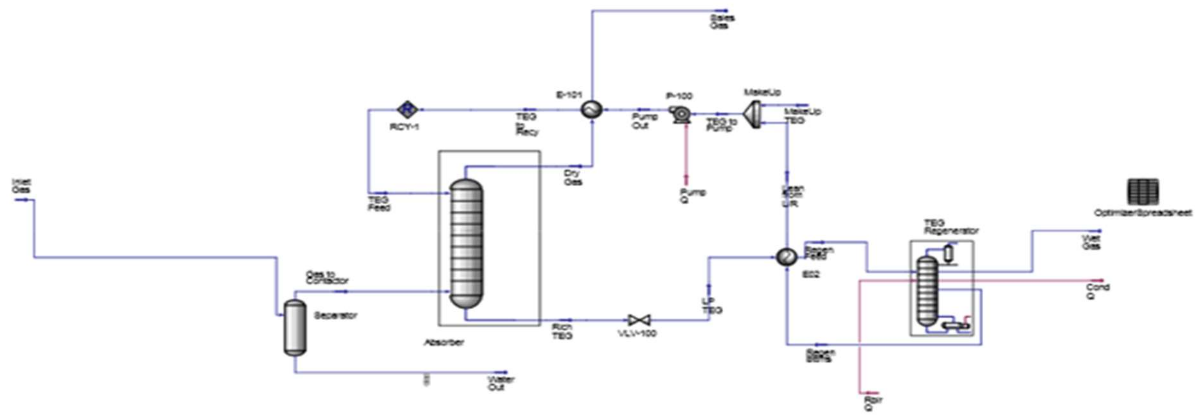

Figure 1: Process Flow Diagram of Natural Gas Dehydration Plant

B. Development of the Dynamic and Control Models of the Process at the Feed Point Section of the TEG Recovery Regenerator

Equation (1) is the conservation principle of mass that is utilized in development of dynamic models of the regenerator unit of a natural gas TEG dehydration plant.

$$[Rate\ of Accumulation of\ \ mass\ inthe\ system\ ] = [Rate\ of inflow of\ mass] - [Rate\ of outflow of\ mass] \pm [Rate\ of operation/depletion of\ mass] \quad (1)$$

The terms in the equation can be defined as follows;

$$[Rate\ of Accumulation of\ mass\ inthe\ system\ ] = \frac{d}{dt}(\rho v) \quad (2)$$

$$[Rate\ of inflow of\ mass] = F_i \rho_i \quad (3)$$

$$[Rate\ of outflow of\ mass] = F\rho \quad (4)$$

$$[Rate\ of operation/depletion of\ mass] = 0 \quad (5)$$

Substituting equation (2) to (5) into equation (1) and further simplification yields

$$\frac{d}{dt}(\rho v) = F_i \rho_i - F\rho \pm 0 \quad (6)$$

For a constant density, equation (6) becomes

$$\frac{dv}{dt} = F_i - F \quad (7)$$

Equation (7) can be expressed in terms of pressure as,

$$\frac{V}{RT}\frac{dp}{dt} = F_0 - F \quad (8)$$

$$\text{Let } a = \frac{V}{RT} \quad (9)$$

$$\frac{adp}{dt} = F_0 - F \quad (10)$$

Equation (10) is the dynamic mass balance in terms of pressure at the regenerator feed point. The dynamic energy balance can also be developed as follows:

$$[Rate\ of accumulation of\ energy\ in\ the\ system\ ] = [Rate\ of\ inflow\ of\ energy] - [Rate\ of outflow of\ energy] \pm [Rate\ of generation/depletion\ of\ energy] +$$

$[Quantity\ of energysupplied\ tothe\ system]$ (11)

The terms in equation (11) can be defined as follows;

$[Rate\ of accumulation of\ energy\ inthe\ system\ ] = \frac{d}{dt}\left(\rho v C_p T\right)$ (12)

$[Rate\ of\ inflow of\ energy] = F_i T_i$ (13)

$[Rate\ of\ outflow of\ energy] = FT$ (14)

$[Rate\ of generation/depletion of\ energy] = 0$ (15)

$[Quantity\ of\ energysupplied\ to\ the\ system] = UA(T - T_C)$ (16)

Substituting equation (12) to (16) into equation (11) yields;

$$\frac{d}{dt}\left(\rho v C_p T\right) = F_i T_i - FT + UA(T - T_C) \quad (17)$$

Simplifying and integrating ideal gas law into equation (17) yields

$$\frac{dT}{dt} = \frac{1}{\rho C_p} \cdot \frac{P_i T_i}{RT\tau} - \frac{1}{\rho C_p} \cdot \frac{PT}{RT\tau} + \frac{UA}{\rho C_p}(T - T_C) \quad (18)$$

$$\text{Let } a_1 = \frac{1}{\rho C_p RT} \quad (19)$$

$$a_2 = \frac{UA}{\rho C_p} \quad (20)$$

$$\frac{dT}{dt} = \frac{a_1}{\tau} P_i T_i - \frac{a_1}{\tau} PT + a_2(T - T_C) \quad (21)$$

Equation (21) is the dynamic energy model as a function of temperature and pressure at the regenerator feed point.

The temperature control model at the regenerator feed point was developed by utilizing Taylor's series expansion principle in linearizing equation (21) and taking Laplace transform of both sides of the model and further simplification to yield;

$$\underline{T}_{(S)} = \frac{K_{PT}}{S(S-K)} - \frac{K_{TC}}{S(S-K)} - \frac{K_P}{S-K} - \frac{\varphi}{\left(S+\frac{1}{\tau}\right)(SK)} \quad (22)$$

Where,

$$K_{PT} = \frac{a_1}{\tau} \rho_i T_i \quad (23)$$

$$K_{TC} = a_2 T_C \quad (24)$$

$$K_P = \frac{a_1}{\tau} P_{SS}^2 \quad (25)$$

$$K_T = \frac{b_1}{\tau} T_{SS}^2 \quad (26)$$

$$K = a_2 + \frac{b}{\tau} \quad (27)$$

$$\varphi = \frac{b_1}{\tau} P_{SS} \quad (28)$$

Where K_{PT} is the PT control constant, K_{TC} is the coolant temperature control constant and K is the constant, K_T is the temperature control model as a function of time can be obtained by taking the inverse Laplace transform of equation (22) and expressing the terms in partial fraction. The solution of the partial fraction gives.

$$T_{(t)} = \left(\frac{K_{TC}}{K} - \frac{K_{PT}}{K} - K_P - K_T\right) e^{kt} + \frac{K_{PT}}{K} - \frac{K_{TC}}{K} - \left(\frac{\tau}{K+1}\right) \varphi\left(e^t - e^{kt}\right) \quad (29)$$

Equation (29) is the temperature control model as a function of time at the feed point of the regenerator. Figure 2 represents the feedback temperature control of the TEG regenerator system.

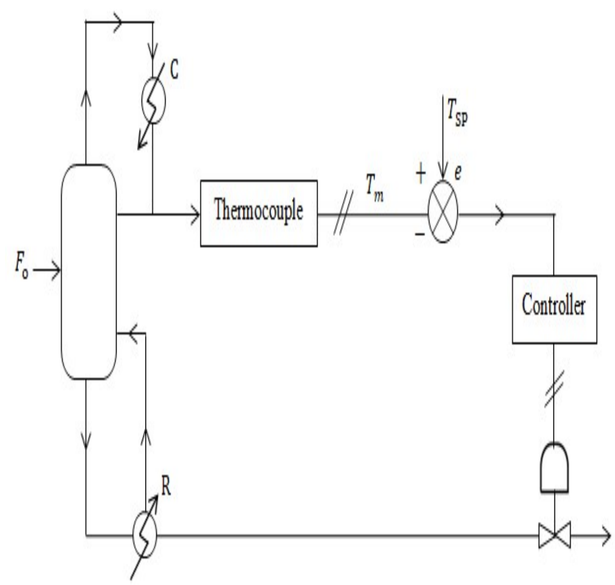

Figure 2: Feedback Temperature Control of TEG Regenerator

The input-output model of the TEG regenerator process for the temperature and pressure control model is represented in Figure 3 below.

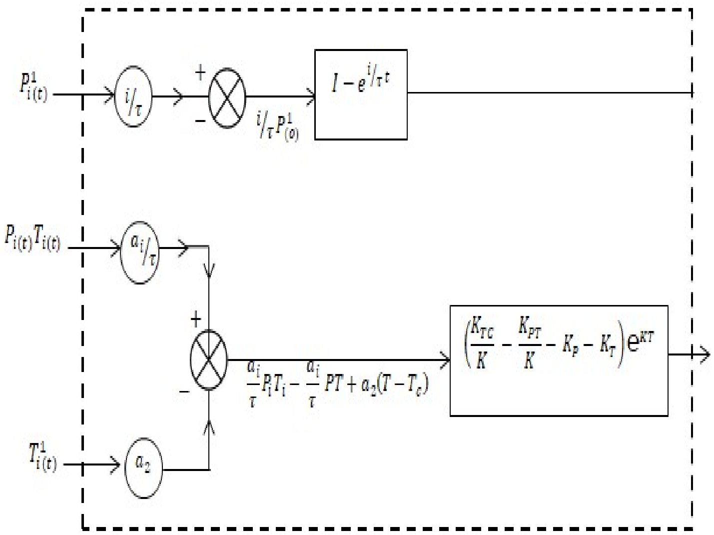

Figure 3: Input-Output Model of TEG Regenerator Process

The PID control configuration which is generally regarded as the best control method and predominantly utilized in industry because of its simplicity, efficiency, and effectiveness is considered the control strategy, and the general response is mathematically expressed as;

$$T^1_{(S)} = \frac{G_{P(S)}G_{F(S)}G_{C(S)}}{1+G_{P(S)}G_{F(S)}G_{C(S)}G_{m(S)}}T_{SP(S)} + \frac{G_{d(S)}T^1_{d(S)}}{1+G_{P(S)}G_{F(S)}G_{C(S)}G_{m(S)}} \quad (30)$$

where,

$$G_{(S)} = G_{P(S)}G_{F(S)}G_{C(S)}G_{m(S)} \quad (31)$$

The transfer function of the process is;

$$G_{P_{1(S)}} = \frac{a_1}{\tau\left(S-a_2-\frac{b}{\tau}\right)} \quad (32)$$

$$G_{P_{2(S)}} = \frac{a_2}{S-a_2-\frac{b}{\tau}} \quad (33)$$

The transfer function of the load or disturbance is given as;

$$G_{d(S)} = \frac{b_1}{\tau\left(S-a_2-\frac{b}{\tau}\right)} \quad (34)$$

The closed-loop response of the regenerator process with feedback control is presented in Figure 4.

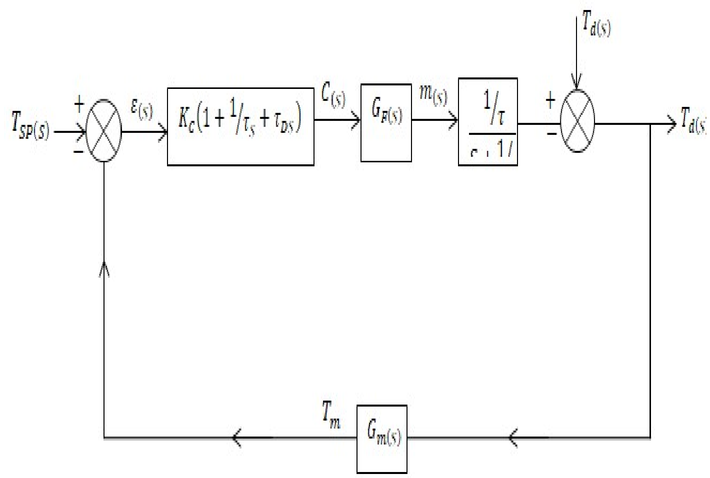

Figure 4: Closed-Loop Response of Regenerator with Feedback Control

C. Development of the Dynamic and Control Models of the Process at the Reboiler Section of the TEG Reboiler Regenerator

Consider the schematic representation of the reboiler section of a TEG regenerator unit of a dehydration plant in Figure 5

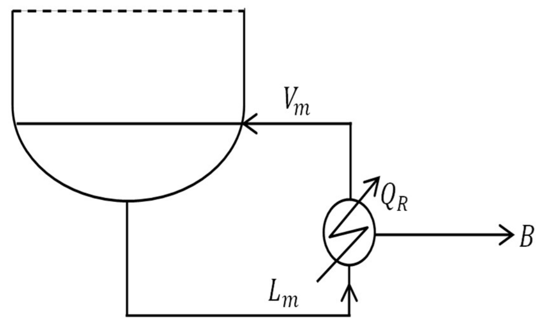

Figure 5: Regenerator Reboiler Section

The principle of energy conservation can be utilized in performing an energy balance on the reboiler section of a TEG recovery regenerator by defining the terms in (ii) as follows;

$[Rate\ of energy\ accumulated\ within\ the\ reboiler]$
$= M_R C_{PR} \frac{dTR}{dt}$ (35)

$[Rate\ of inflow\ to\ the\ reboiler] =$
$L_M M_B C_{Pm} T_m$ (36)

$[Rate\ of outflow\ from\ the\ reboiler] =$
$B_{MB} C_{PB} T_B + V_m M_V C_{Pv} T_R$ (37)

No generator/depletion of energy and energy supply occurs in the reboiler section. Therefore, equation (35) to (37) can be combined in equation (ii) to give.

$M_R C_{PR} \frac{dTR}{dt} = L_M M_B C_{Pm} T_m - B_{MB} C_{PB} T_B -$
$V_m M_V C_{Pv} T_R$ (38)

Dividing equation (38) by $M_R C_{PR}$ and further simplification yields;

$\frac{dTR}{dt} + \frac{I}{\tau v} T_R = \frac{I}{\tau m} T_m - \frac{I}{\tau B} T_B$ (39)

Where equation (39) is the dynamic model of the regenerator bottom and can be expressed in terms of deviation variables as follows;

$\frac{dT^1}{dt} + \frac{1}{\tau v} T_R^1 = \frac{1}{\tau m} T_m^1 - \frac{1}{\tau B} T_B^1$ (40)

where

$T_R^1 = T_R - T_{R,S}$ (41)

$T_M^1 = T_M - T_{M,S}$ (42)

$T_B^1 = T_B - T_{B,S}$ (43)

The control model of the reboiler section of the regenerator section of the regenerator can be obtained by transforming equation (40) in the S-domain by Laplace transform application as;

$\underline{T}_{R(s)} = \left(\frac{\frac{1}{\tau_m}}{S+\frac{1}{\tau_v}}\right) \underline{T}_{M(s)} - \left(\frac{\frac{1}{\tau_B}}{S+\frac{1}{\tau_v}}\right) \underline{T}_{B(s)}$ (44)

For a step and sinusoidal function and application of partial fraction in the model resolution gives the process control model of the reboiler temperature as a function of temperature as follows;

$\underline{T}_{R(t)} = 0.981(1 - e^{-0.0157t}) -$
$0.0142 T_B e^{-0.0157t}$

(45)

$\underline{T}_{R(t)} = 0.981(e^{-0.0157t} + cost) +$
$4.2x10^{-6}\ sint - 0.0142 T_B e^{-0.0157t}$

(46)

The transfer functions of the process and disturbance variables are expressed mathematically as;

$G_{p(s)} = \frac{\frac{1}{\tau m}}{s+\frac{1}{\tau v}}$ (47)

$G_{d(s)} = \frac{\frac{1}{\tau B}}{s+\frac{1}{\tau v}}$ (48)

D. Data for Simulation

The data used for the simulation of the natural gas TEG dehydration process were obtained from the literature showing the characterized natural components, composition, molar mass, and HYSYS simulation operating condition as shown in Table 1

Table 1 shows the natural gas properties

Components	Composition	Molar mass (g/
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_20	0.0050	18.00
N_2	0.0010	14.00
H_2s	0.0155	34.00
C_{0_2}	0.0284	44.00
TEG	0.0000	150.154
Total	1.0000	610.894
Operating Condition		
Pressure (KPa)	6205.2832	
Temperature (°C)	29.4444	
Flow rate (kg/s)	768.6343	

Source: [9]

III. Results and Discussion

A. Results of TEG Recovery Regenerator Control

The control analysis of the TEG recovery regenerator was considered at the feed point and bottom (reboiler) of the regenerator. The behaviour of the process was analyzed in terms of an open loop without disturbance, an open loop with disturbance and a closed loop for both manual and automatic PID control configurations.

B. Results of Open Loop without Disturbance at the Feed Point of the Regenerator

Figure 5 shows the profile of temperature and time of the open loop system without disturbance at the feed point of a TEG recovery regenerator. From the plot, the feed temperature of the regenerator increases exponentially as the time increases during the process since the feed temperature of the TEG and water mixture is usually well below 98.9^{0}C which implies that separation of TEG and water occurs within a short period.

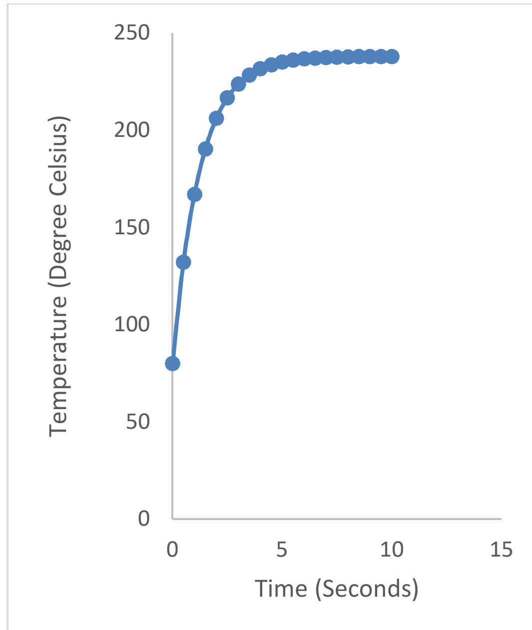

Figure 5: Profile of Temperature and Time of an Open-Loop without Disturbance

C. Result of Open Loop System with Disturbance at the Feed Point

Figure 6 is a profile of the temperature and time of open loop configuration with disturbance at the feed point of a TEG recovery regenerator process of a dehydration system. According to the plot, the presence or introduction of a disturbance at the feed point makes the system or process behave uncontrollably as demonstrated by the sinusoidal or wavelike displacement of the feed temperature relationship with time. This is an indication that the process will require a much longer time to attain its stability thereby, necessitating the configuration of a certified or appropriate controller for optimum performance or yield.

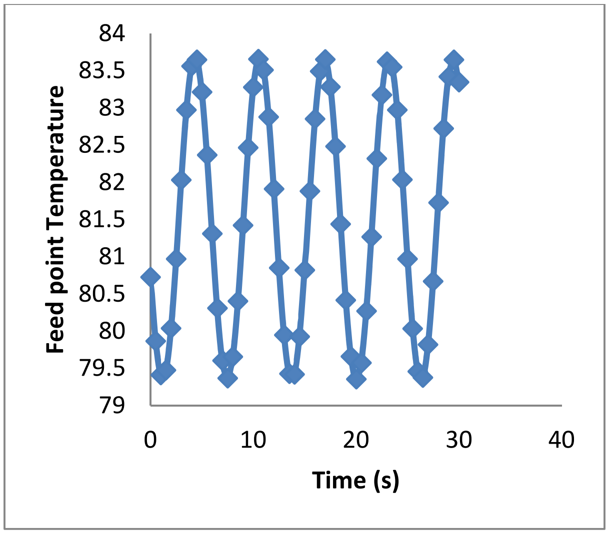

Figure 6: Uncontrolled Temperature profile for a feed point versus Time in Distillation Column

D. Result of Closed-Loop Block Diagram for Temperature Control at the Feed Point of a TEG Recovery Regenerator

Figure 7 is a closed loop block diagram for temperature control at the feed point of a TEG recovery regenerator with a configured thermocouple as the control device. This block diagram was obtained from the advanced process simulation tool Simulink to generate or develop temperature control profiles with time at various controller parameters or gains which demonstrates the difference between manual and automatic tuning of control parameters for the determination of TEG recovery process stability at the feed point of the regenerator.

E. Closed Loop Temperature Control at Regenerator Feed Point

The profiles below show the results of closed-loop temperature control at the feed point of a TEG recovery regenerator during a natural gas dehydration process. These profiles were generated from the manual tuning of various PID controller parameters or gains.

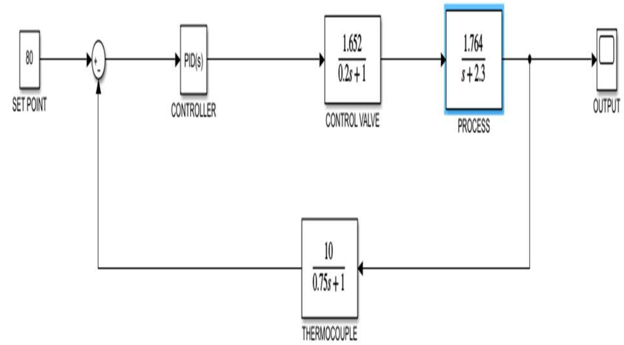

Figure 7: Closed Loop Block Diagram for Temperature Control at Regenerator Feed Point

F. Result of Temperature Control at Feed Point with Controller Gains of 1.5, 0.25 and 1

Figure 8 is a plot of temperature control with time at the regenerator feed point by manual tuning of controller parameters PID of 1.5, 0.25 and 1 in a feedback control configuration. According to the plot, there was a high level of instability in the process between the initial and final temperature and time respectively as a result of the disturbance in the system.

G. Result of Closed Loop Temperature Control at Controller Gains of 0.2, 1.2 and 1.5

Figure 9 is a representation of temperature control and time profile at the feed point of a TEG recovery regenerator during a dehydration process. Here, the effect or changes in temperature over time were investigated by manually tuning controller parameters or gains of 0.2, 1.2 and 1.5 for K_P, K_I and respectively in a closed loop controller mechanism. The resultant effect of this tuning

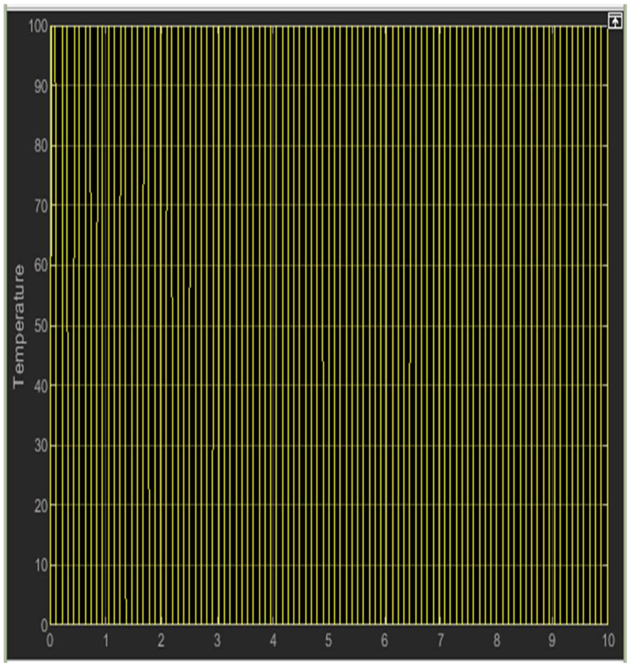

Figure 8: Plot of Temperature Control and Time at Regenerator Feed Point with PID Controller of 1.5, 0.25 and 1

The profile showed a high level of instability as indicated by the maximum displacement of a wavelike motion in the profile

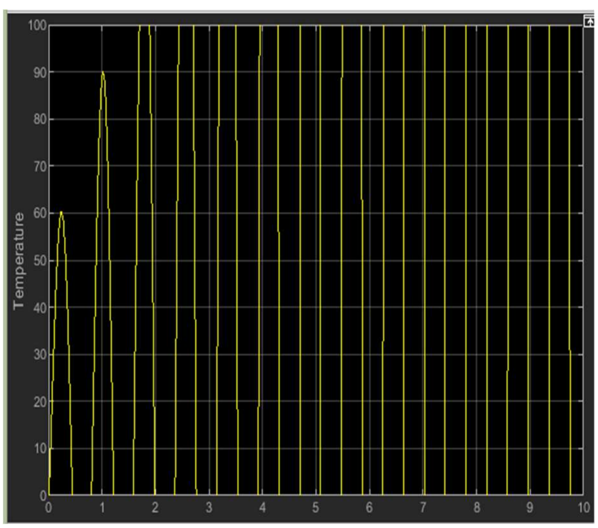

Figure 9: Profile of Temperature Control Versus Time at Regenerator Feed Point Tuned at PID Controller Gains of 0.2, 1.2, and 1.5

H. Result of Temperature Control at Feed Point with Controller Gains of 1.5, 3.5 and 2.5

Figure 10 is a profile of temperature control at various times at the feed point of a TEG recovery regenerator with a turning of controller parameters of 1.5, 3.5, and 2.5 for K_P, $K_{I,}$ and K_D respectively in a feedback controller configuration system. According to the plot, the process experienced a massive disturbance which resulted in a high level of instability which was gradually reduced as the time increased but failed to attain its stability at the end time of 10 seconds. However, an increase in the process time as the feed temperature decreases with result in system or process stability as a result of the continuous tuning effect.

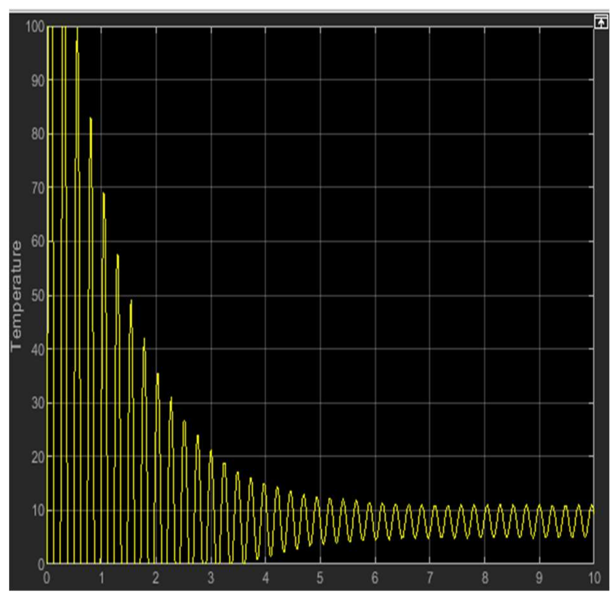

Figure 10: Profile of Temperature Control Versus Time at Regenerator Feed Point with PID Controller of 1.5, 3.5, and 2.5

I. Result of Closed Loop Temperature Control at Controller Gains of 0.5, 1 and 1

Figure 11 is a profile or relationship between temperature control over time by manually tuning controller gains of 0.5, 1 and 1 for K_P, K_I and K_D respectively in a closed-loop feedback controller mechanism during a TEG recovery process in a regenerator. From the plot, the process exhibited a high level of instability as indicated by the wavelike displacement between the dead or start time to 3.5 seconds before attaining stability at a very low temperature of less than 10^0C between 3.5 seconds to 10 seconds which is not up to the specification or requirement of feed condition for optimum performance

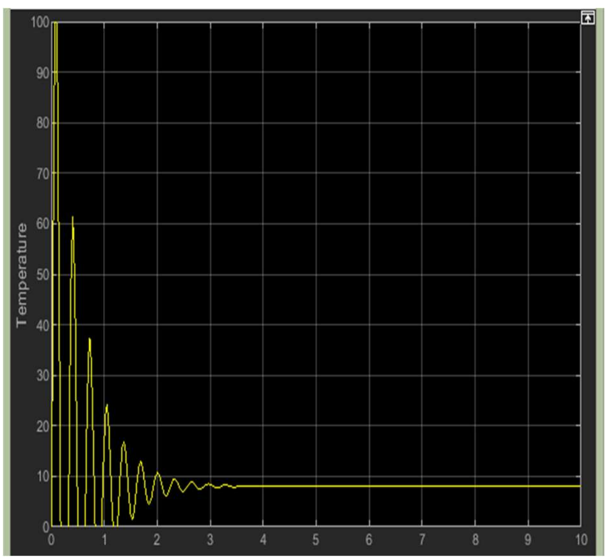

Figure 11: Profile of Temperature Control Versus Time at Regenerator Feed Point Tuned at PID Controller Gains of 0.5, 1, and 1

J. Result of Temperature Control at Feed Point with Controller Gains of 1, 0.5 and 1

Figure 12 shows the plot of temperature control with time at the regenerator feed point which was tuned manually in a closed-loop system configuration at controller gains of 1, 0.5, and 1 for K_P, k_I, and K_D respectively. According to the plot, there was massive disturbance during the process between the temperature of 0^0C to 74^0C and time of 0 seconds to 1.5 seconds with a significant reduction of the disturbance between 0^0C to 9^0C and time 1.5 seconds to 3.6 seconds. The process attained its stability at the temperature of 9^0C and between 3.6 seconds to 10 seconds as a result of the manual turning effect of the controller.

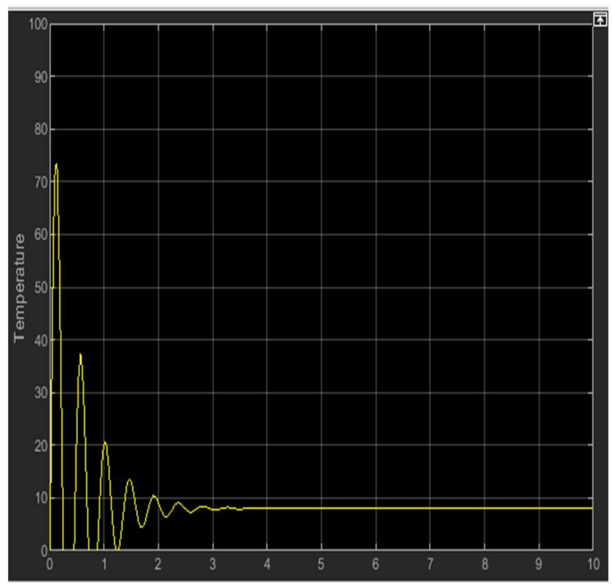

Figure 12: Plot of Temperature Control against Time at Regenerator Feed Point with PID Controller of 1, 0.5, and 1

K. Result of Automatic Temperature Control for Closed Loop at Regenerator Feed Point

Figure 13 is a profile of automatic temperature control with time at the feed point of a TEG recovery regenerator for desired controller gains of 1.438, 2.733, and 0.1864 for K_P, K_I, and K_D respectively tuned 402.5 times before attaining its steady state at 4 seconds. Unlike, figures 4.7 to 4.11 obtained from manual tuning, this process reaches its steady state in the shortest possible time. This implies that the process stability is achieved at 4 seconds which is the optimum or desired time at a set point temperature of 80^0C for the process to be controlled using a PID controller.

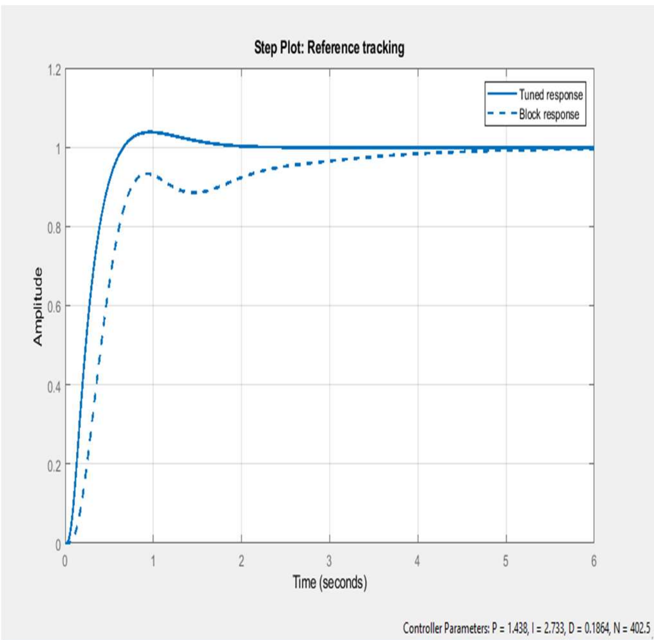

Figure 13: Profile of Automatic Temperature Control and Time at Regenerator Feed Point

L. Results of Open Loop System without Disturbance at the Regenerator Bottom (Reboiler Section).

Figure 14. is a plot of the temperature and time of a TEG recovery regenerator bottom or reboiler section without disturbance or fluctuations of the reboiler operating temperature of 204^0C.According to the plot, there is a linear decrease in the reboiler operating temperature as time increases during the process. This is an indication that any disturbance or fluctuation of the feed rate of the regenerator will alter or influence the reboiler operating temperature and the time required during the process.

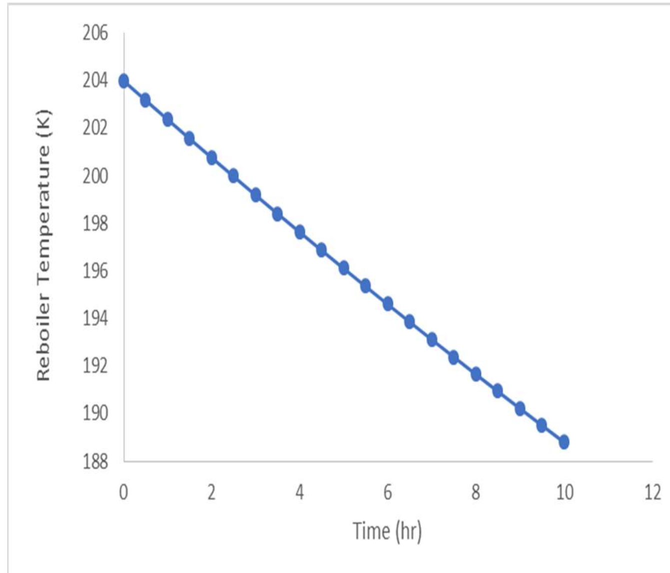

Figure 14: Plot of Temperature and Time at Regenerator Bottom without Disturbance

M. Results of Open Loop System with Disturbance at the Regenerator Bottoms (Reboiler Section)

Figure 15 is a plot of the reboiler operating temperature and time of a TEG regeneration process. According to the plot changes (increase or decrease) of the reboiler or bottom temperature of the regenerator will affect the behaviour of the process or system as shown in the sinusoidal or wavelike uncontrolled profile of temperature over time. This is an indication that the system will require a much longer time before attaining its stability, thereby necessitating the configuration of a certified or suitablecontroller for optimum performance or yield of TEG during the process.

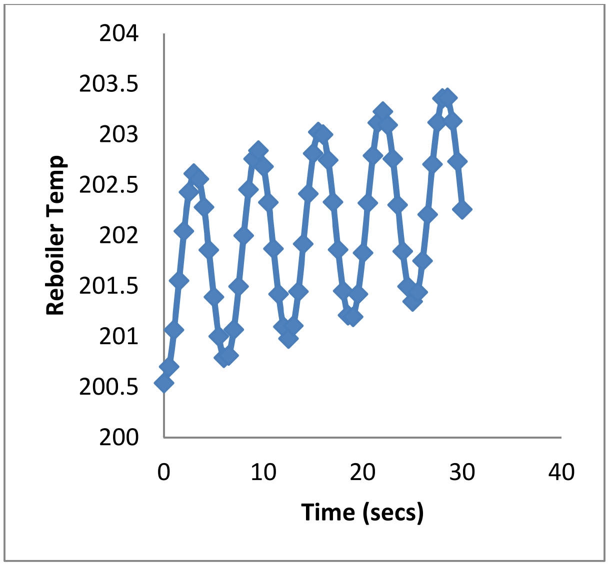

Figure 15: Uncontrolled Temperature Profile for a Reboiler versus Time in Distillation Column

N. Results of Closed Loop Control Configure at Bottom of TEG Recovery Regenerator.

The results of temperature control with time of a closed loop blocked diagram and control configuration at the bottom or reboiler section of a TEG recovery regenerator process at various controller parameters (PID) for both manual and automatic tuning are presented as follows.

O. Result of Closed-Loop Block Diagram for Temperature Control at the Bottom of a TEG Recovery Regenerator

Figure 16 is a closed loop block diagram feedback of temperature response with a configured thermocouple as the controller device utility during a TEG recovery process was obtained from advanced process simulation tool simulation to generate temperature control and time profiles at various controller going of parameters which accounts for the difference between manual tuning and automated control tuning for determination of the TEG recovery process stability of temperature at optimum or shortest possible time.

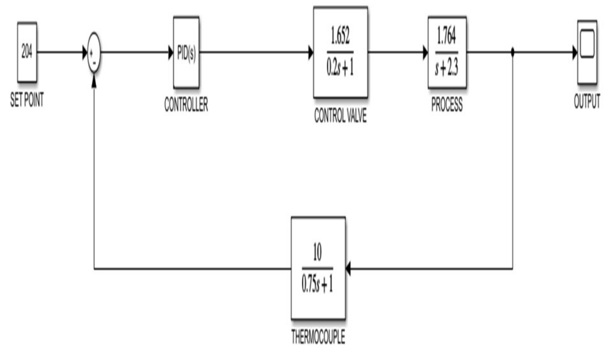

Figure 16: Closed Loop Block Diagram for Temperature Control at Regenerator Bottom

P. Closed Loop Temperature Control at Regenerator Bottom with Controller Gains of 1, 1, and 0

Figure 17: represents a temperature control and time profile of the TEG recovery process in a regenerator of a dehydration plant. Here the effect of temperature variation over time during the process was investigated at the bottom of the regenerator using the manual tuning of controller gains 1, 1, and 0 for K_P, K_I, and K_D respectively in a closed loop controller mechanism. The effect of tuning on temperature over time indicates a high level of instability, meaning that the process occurs uncontrollably as shown by the high displacement of the wavelike motion in the profile.

Q. Closed Loop Temperature Control at Regenerator Bottom with Controller Gains of 2, 0.5 and 1

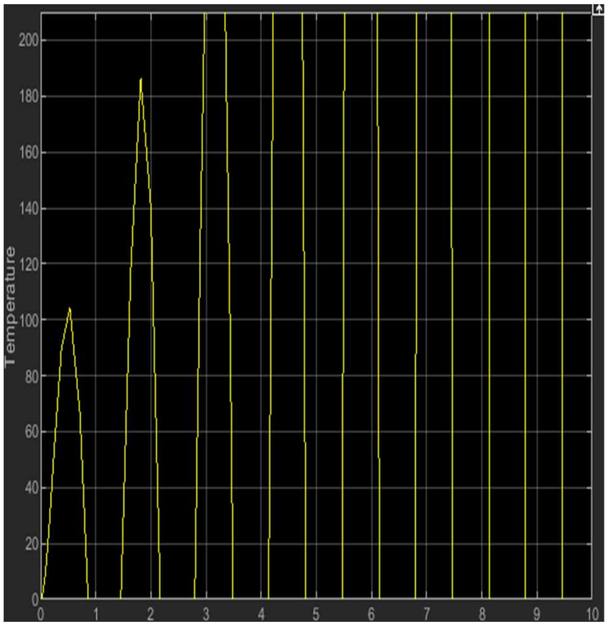

Figure 17: Plot of Temperature Control and Time at Regenerator Bottom with PID Controller of 1, 1, and 0

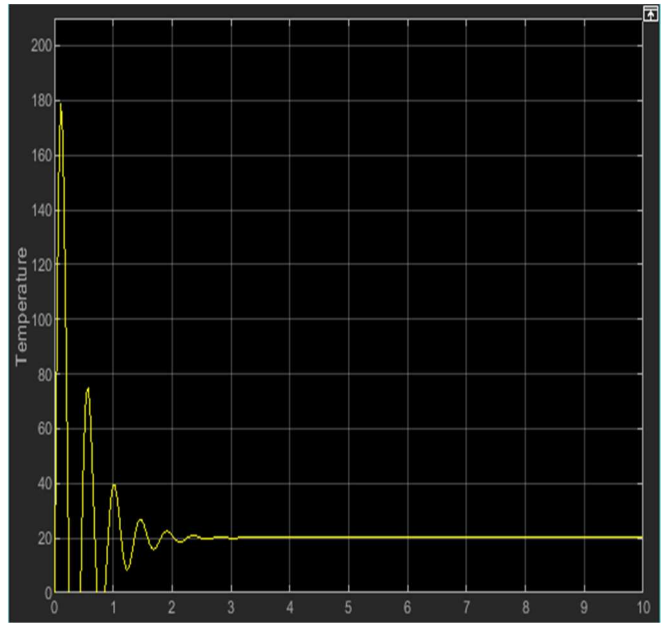

Figure 18: Plot of Temperature Control and Time at Regenerator Bottom with PID Controller of 2, 0.5 and 1

Figure 18 is a plot or graph of temperature control and time variation or behaviour during a TEG recovery process in a regenerator of a dehydration plant. Here, the controller parameters or gains of 2, 0.5, and 1 for K_P, K_I, and K_D respectively were tuned manually in a closed-loop control system configuration, and the process behaviour was investigated and displayed on the profile. According to the plot between the initial temperature of 0^0C and 179^0C at a time o to 2.3 seconds the process exhibited a high level of turbulence or disorderliness due to disturbances introduced by the manual tuning process of controller gains. The process, however, attained its stability at a temperature of 20^0C between 3 to 10 seconds as shown on the profile.

R. Closed Loop Temperature Control at Regenerator Bottom with Controller Gains of 1, 1, and 1

Figure 19 is a representation of temperature control and time profile in a TEG recovery regenerator of a dehydration process. Here, the manual tuning of the PID with controller parameters or gains of 1, 1 and 1 respectively in a closed loop feedback system shows a massive disturbance or disorderliness of the process at a temperature range of 0^OC to 170^0C within the time of 0 to 2 seconds. Also, between time 2 to 3.4 seconds and a temperature of 20^0C, the process became slightly unstable, and from a time of 3.4 to 10 seconds with a temperature of 20^0C the process attained its stability.

S. Result of Automatic Temperature Control for Closed Loop at Regenerator Bottom

Figure20 is a plot of automatic temperature control with time at the bottom or reboiler section of the TEG recovery regenerator for desired controller gains of 0.1773 0.1665 and 0.04408 for K_P,K_I, and K_D respectively tuned 205.3 times before attaining its steady

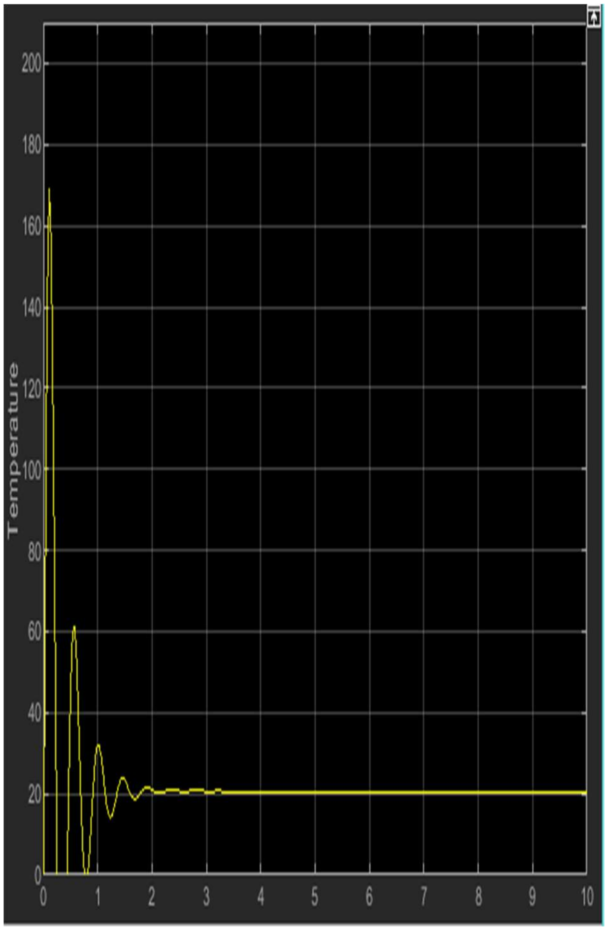

Figure 19: Plot of Temperature Control and Time at Regenerator Bottom with PID Controller of 1, 1, and 1

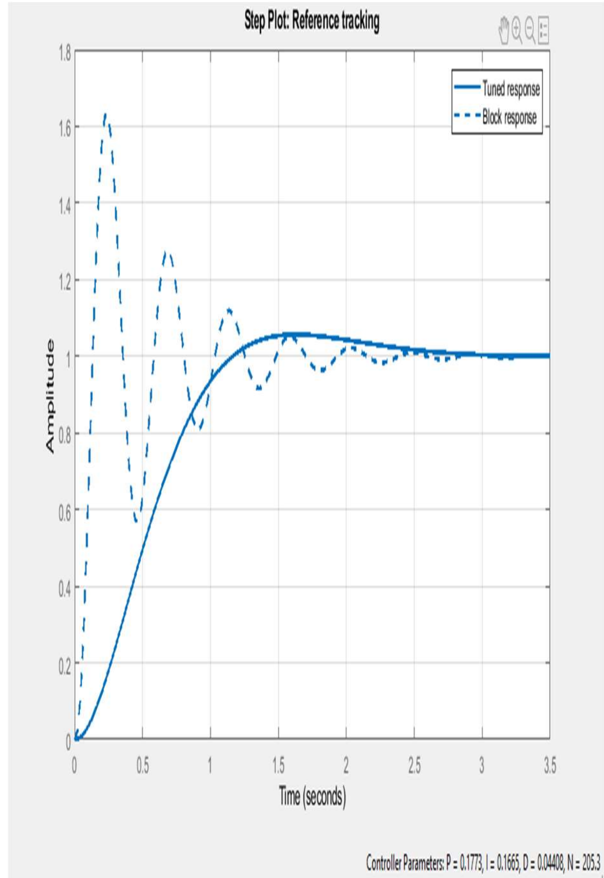

Figure 20: Profile of Automatic Temperature Control and Time at Regenerator Feed Point

state at 2.5 seconds. However, a comparative analysis between the automatic tuning and manual tuning as shown in figures 16 to 18 shows that the automatic tuning gives a better performance result within the shortest possible or optimum time of 2.5 seconds at a set point temperature of 204^0C for the process to be controlled using PID controller .

IV. Conclusion

The research considered the use of the principles of conservation of mass and energy balance in the development of unsteady/dynamic state models at the field point and bottom section of the TEG recovery regenerator of the natural gas dehydration plant. The developed model is characterized by the capability of predicting changes or variations in temperature during the TEG regeneration process due to the configuration of a reboiler and condenser in the unit. The natural gas TEG dehydration plant was designed using HYSYS while the temperature control analysis was performed at the foid point and bottom (reboiler) of the regenerator in terms of open loop and closed loop for both manual and automated PID control configurations using Simulink. The effect of the process variable (Temperature) was measured using a thermocouple configured in the system. The stability response of the manual and automated tuning of PID controller gains showed that the system attained its stability within a short period using automated tuning compared to the use of manual tuning of controller parameters or gains. Hence, for efficiency and optimum performance of the TEG dehydration plant, the TEG recovery generator should be configured with the automated controller.

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