International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2013): 6.14 | Impact Factor (2013): 4.438

Modeling and Control of the Crude Atmospheric Unit in Khartoum Refinery

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Abstract: ***The work undertaken, lead to a mathematical model of the distillation column that can separate multicomponent systems in Khartoum refinery. Software was developed and might be used for research and development as well as at the stage of starting – up and shut down periods. A case study taking Distillation Column Units (DCU) of Khartoum Refinery was studied and investigated. This work investigates the experimental data for the equilibrium of the Nile blend crude was determined. The equilibrium data were correlated (using short cut methods) and an equilibrium model was constructed. This model coupled with a multicomponent material balance was used for the determination of the number of theoretical stages, stage efficiency, and composition and temperature profiles. Three transfer functions around the condenser, the re boiler and the feed plate were determined. Software of MATLAB 7 was used to analyze the system stability; these were Nyquist diagram, Bode plot and Routh Hurwtz. The transfer functions of the reboiler, condenser, and feed plate were obtained. From the transfer functions created Nyquist diagrams, Bode plots, were converted from Laplace domain to Z domain, using MATLAB7 Software. A closed loop control strategy for the system was recommended.***

Keywords: Equilibrium; Distillation; Matlab; Multi-components; Software; Condenser

1. Introduction

1.1 Distillation Column Model Formulation

Distillation is the most popular and important separation method in the petroleum industries for purification of final products. Distillation columns are made up of several components, each of which is used either to transfer heat energy or to enhance mass transfer. [1]

In forming a model for the distillation column, general assumptions about the operation of a distillation column must be made. The assumptions a model makes are the major distinctions between the models found in the distillation literature. A complete set of dynamic equations would be of a daunting size considering that a stage contains many forms of energy transformations and that a distillation column or a set of columns can contain hundreds of stages. Of course, simplifying assumptions are desirable in such a complex apparatus [2], [3], [4].

Model specifications are re-used in the design evaluation of large integrated processes and control systems. In addition, the models once made are used to support operator training. Computerized dynamic simulation models are useful for verification of both conceptual and detailed process designs. They make in-house pre-testing of automation systems, user interfaces, and operational procedures possible, as well. They are used for generic teaching and learning of basic principles, detailed pre-training of new personnel, and re-training of experienced operators. [5]

Improved distillation control is characterized by a reduction in the variability of the impurities in the products. Meeting the specification requirements on the variability of final products can make the difference between the product being a high value-added product with large market demand and being a low-valued product with a small market demand [6].

1.2 Optimum Design of Plate

Calming zones are used for drop forth velocity, for smoothly in let in down comer. [7]

1.2.1 Flooding

Flow rate is depend on difference pressure (Δp)in tower, when increased over proper level and to be high than the flow is to be impossible in tower and the liquid is perhaps in zones and the tower then a unstable process. [7]

1.2.2 Weeping

The lower limit of the operating range when liquid leakage through the holes becomes excessive. The vapor velocity at the weep point is the minimum value for stable operation. The hole area must be chosen so that at lowest operating rate the vapor flow velocity is still well above the weep point. [7]

1.2.3 Entrainment

Entrainment can be estimated from the correlation given by Fair1961, which gives the fractional (kg/kg gross liquid flow) as a function of the liquid – vapor factor F_{Lv}. With the percentage approach to flooding as a parameter. [7]

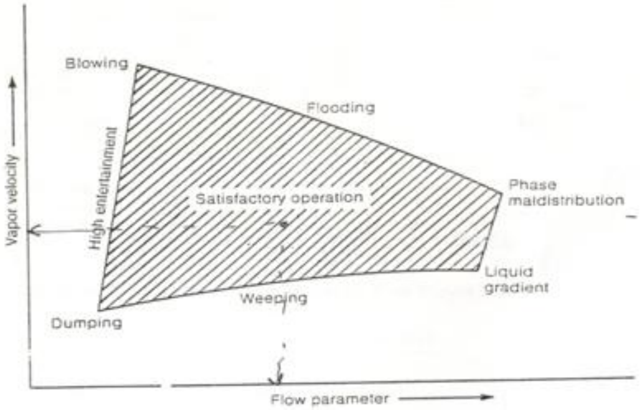

Figure 1: Zone of satisfactory operation for plate columns [7]

1.3 Material of Construction

Material of construction of the tower and trays is carbon steel because has long period in operation but it's expensive.

2. Models Section

2.1 Development of transfer function

Transfer function is an expression that represents the functional relationship between the input to any particular element and that output from that element.

It relates the input – output pair of variables and it indicates the dynamic response of the system component or elements.

The transfer function, G, is the ratio of output to the input, or the ratio of their Laplace transforms and is generally defined as:
G = Y (Laplace Transform of output)/X (Laplace Transform of input)

The transfer function, G, may be a constant or an operator or any combination of them. [8]

2.1.1 Re boiler transfer function

Feed m_0, Θ_0

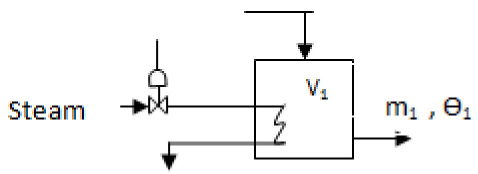

Figure 2: Energy balance around re boiler

(1)

$$v_1 \delta cp \frac{\partial \theta_1}{\partial t} = q + mcp\theta_0 - mcp\theta_1$$

Divided by mCp

(2) $$\frac{v_1 \delta}{m} \frac{\partial \theta_1}{\partial t} = \frac{q}{mcp} + \theta_0 - \theta_1$$

(3)

$$\frac{v_1 \delta}{m} \frac{\partial \theta_1}{\partial t} + \theta_1 = \frac{q}{mcp} + \theta_0$$

Put

(4) $$\frac{v_1 \delta}{m} = \tau$$

(5) $$\tau \frac{\partial \theta_1^{\wedge}}{\partial t} + \theta_1^{\wedge} = \frac{q^{\wedge}}{mcp} + \theta_0^{\wedge}$$

(6)

$$\tau_s \theta_1(s) + \theta_1(s) = \frac{\varphi}{mcp} + \theta_0(s)$$

$$\theta_1(s)(\tau_s + 1) = \frac{\varphi}{mcp} + \theta_0(s)$$

(7)

(8)

$$\theta_1(s) = \frac{\varphi}{mcp(\tau_s + 1)} + \frac{\theta_0(s)}{(\tau_s + 1)}$$

(9) $$\frac{\theta_1(s)}{\theta_0(s)} = \frac{\varphi}{mcp(\tau_s + 1)\theta_0(s)} + \frac{1}{(\tau_s + 1)}$$

$$\frac{(\tau\varphi + \tau mcp\theta_0)s + (\varphi + \mathrm{mcp}\theta_0)}{s^2 + \frac{2}{\tau s} + \frac{1}{\tau^2}}$$

Using MATLAB to find the transfer function
Num= $[(\tau\varphi + \tau mcp\theta_0)(\varphi + mcp\theta_0)]$
Den=$\left[1 \ \frac{2}{\tau} \ \frac{1}{\tau^2}\right]$

Condenser Transfer Function 2.1.2

Feed m_0, Θ_0

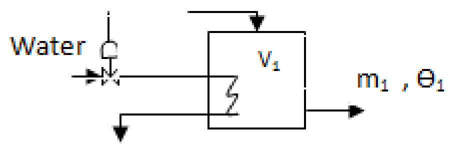

Figure3: Energy balance around condenser

(10)

$$v_1 \delta cp \frac{\partial \theta_1}{\partial t} = -q - mcp\theta_0 - mcp\theta_1$$

Divided by mCp

(11)

$$\frac{v_1 \delta}{m} \frac{\partial \theta_1}{\partial t} = -\frac{q}{mcp} - \theta_0 - \theta_1$$

$$\frac{v_1 \delta}{m} \frac{\partial \theta_1}{\partial t} + \theta_1 = -\frac{q}{mcp} - \theta_0$$

(12)

Put

(13) $$\frac{v_1\delta}{m} = \tau$$

(14)
$$\tau\frac{\partial\theta_1^\wedge}{\partial t} + \theta_1^\wedge = -\frac{q^\wedge}{mcp} - \theta_0^\wedge$$

(15) $$\tau_s\theta_1(s)+\theta_1(s) = -\frac{\varphi}{mcp} - \theta_0(s)$$

(16)
$$\theta_1(s)(\tau_s+1) = -\frac{\varphi}{mcp} - \theta_0(s)$$

(17)
$$\theta_1(s) = -\frac{\varphi}{mcp(\tau_s+1)} - \frac{\theta_0(s)}{(\tau_s+1)}$$

(18) $$\frac{\theta_1(s)}{\theta_0(s)} = -\frac{\varphi}{mcp(\tau_s+1)\theta_0(s)} - \frac{1}{(\tau_s+1)}$$

$$\frac{(\tau\varphi - \tau mcp\theta_0)s - (mcp\theta_0 - \varphi)}{s^2 + \frac{2}{\tau s} + \frac{1}{\tau^2}}$$

Num= $[(\tau\varphi - \tau mcp\theta_0)(mcp\theta_0 - \varphi)]$

Den= $\left[1\ \frac{2}{\tau}\ \frac{1}{\tau^2}\right]$

2.1.3 Feed Plate Transfer Function

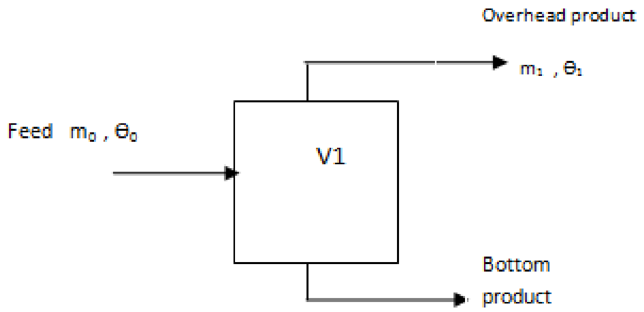

Figure 4: Energy balance around feed plates

(19)
$$v_1\delta cp\frac{\partial(\theta_1-\theta_2)}{\partial t} = q_{re.} - q_{co.} + mcp\theta_0 + mcp\theta_1 - mcp\theta_2$$

Divided by mCp

(20)
$$\frac{v_1\delta}{m}\frac{\partial(\theta_1-\theta_2)}{\partial t} = \frac{q_{re.}}{mcp} - \frac{q_{co.}}{mcp} + \theta_0 + \theta_1 - \theta_2$$

Put

$$\tau = \frac{v\,\delta}{m} \quad (21)$$

$$\tau\frac{\partial(\theta_1-\theta_2)^\wedge}{\partial t} = \frac{q_{re.}{}^\wedge}{mcp} - \frac{q_{co.}{}^\wedge}{mcp} + \theta_0{}^\wedge + \theta_1{}^\wedge - \theta_2{}^\wedge \quad (22)$$

(23) $$\tau_s(\theta_1-\theta_2)(s) = \frac{\varphi_{re.}}{mcp} - \frac{\varphi_{co.}}{mcp} + \theta_0(s) + \theta_1(s) - \theta_2(s)$$

(24)
$$(\theta_1-\theta_2)(s)(\tau_s+1) = \frac{\varphi_{re.}}{mcp} - \frac{\varphi_{co.}}{mcp} + \theta_0(s)$$

(25) $$(\theta_1-\theta_2)(s) = \frac{\varphi_{re.}}{mcp(\tau_s+1)} - \frac{\varphi_{co.}}{mcp(\tau_s+1)} + \frac{\theta_0(s)}{(\tau_s+1)}$$

(26)
$$\frac{(\theta_1-\theta_2)(s)}{\theta_0(s)} = \frac{\varphi_{re.}}{mcp(\tau_s+1)\theta_0(s)} - \frac{\varphi_{co}.}{mcp(\tau_s+1)\theta_0(s)} + \frac{1}{(\tau_s+1)}$$

$$\frac{(\varphi re.\tau - \varphi co.\tau + mcp\theta_0\tau)s^2 + (2\varphi re. - 2\varphi co. + mcp\theta_0)s + \frac{(\varphi re. - \varphi co. + mcp\theta_0)}{\tau}}{\tau^2 mcp\theta_0 s^3 + (2\tau\theta_0 mcp + \theta_0 mcp\tau)s^2 + 3\theta_0 mcps + \frac{\theta_0 mcp}{\tau}}$$

Num=
$(\varphi re.\tau - \varphi co.\tau + mcp\theta_0\tau)s^2 +$
$(2\varphi re. - 2\varphi co. + mcp\theta_0)s + \frac{(\varphi re. - \varphi co. + mcp\ \theta_0)}{\tau}$

Den = $\left(1\ \frac{3}{\tau}\ \frac{1}{\tau^3}\ \frac{3}{\tau^2}\right)$

3. Results and Discussions

3.1 Reboile Transfer Function

Convert to discrete or digital scheme

$= numDZ$
0.1993 − 0.1998 0
$= denDZ$
0.9950 1.9950 − 1.000
The transfer function is:

$$\frac{s + 0.1993}{s^2 + 1.995\, s + 0.995}$$

By this equation we obtained negative roots there for the system is stable.

Result Z-Plane

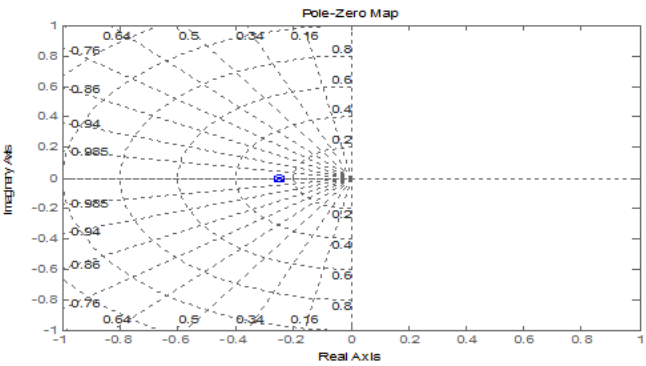

Figure 5: Z – Plane

3.1.1 Result Nyquist Diagrams

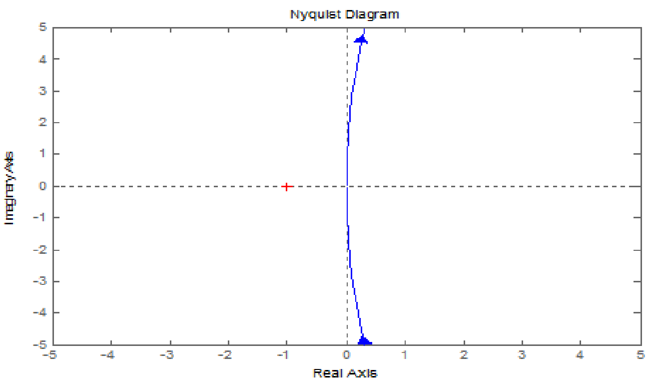

Figure 6: Nyquist Diagrams

3.1.2 Result Bode Plots

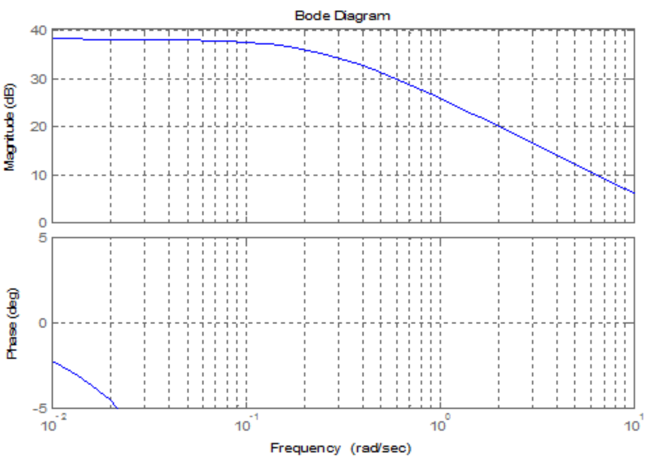

Figure7: Bode Plots

3.2 Condenser Transfer Function

Result converts to discrete or digital scheme

$= numDZ$
$0.1993\ 0.1998 -\ 0$

$= denDZ$
$0.9950\ 1.9950 -\ 1.000$

Transfer function

$$\frac{s + 0.1993}{s^2 + 1.995\, s + 0.995}$$

By this equation we obtained negative roots there for the system is stable.

Result Z - plane

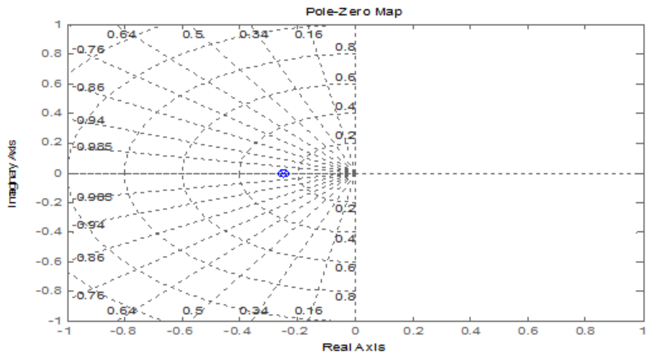

Figure 8: Z – plane

Once the plot lay in left side the system is stable.

3.2.1 Result Nyquist Diagrams

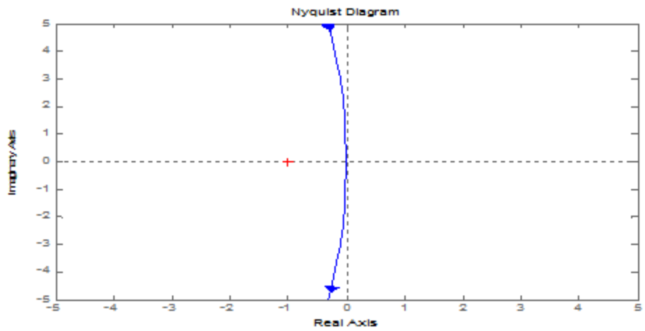

Figure 9: Nyquist Diagrams

3.2.2 Result Bode Plots

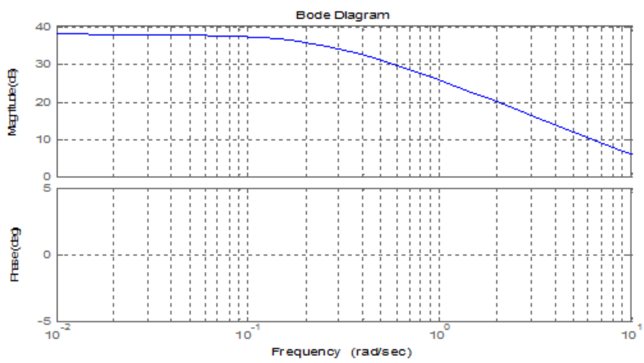

Figure 10: Bode Plots

International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2013): 6.14 | Impact Factor (2013): 4.438

3.3 Feed Plate Transfer Function

Result converts to discrete or digital scheme

$= numDZ$
$0.0498\ 0.0997 - \ 0.0500\ 0$
$= denDZ$
$0.9940 - \ 2.9880\ 2.9940 - \ 1.000$
Transfer function

$$\frac{s^2 + 0.0997s + 0.04975}{s^3 + 2.994s^2 + 2.988s - 0.994}$$

By this equation we obtained negative roots there for the system is stable.

Result Z – plane

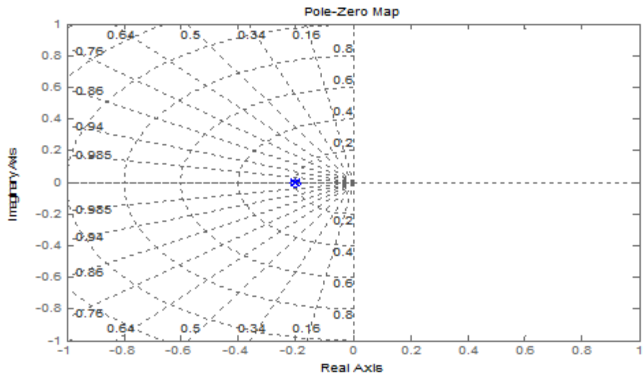

Figure 11: Z – plane

Once the plot lay in left side the system is stable.

3.3.1 Result Nyquist Diagrams

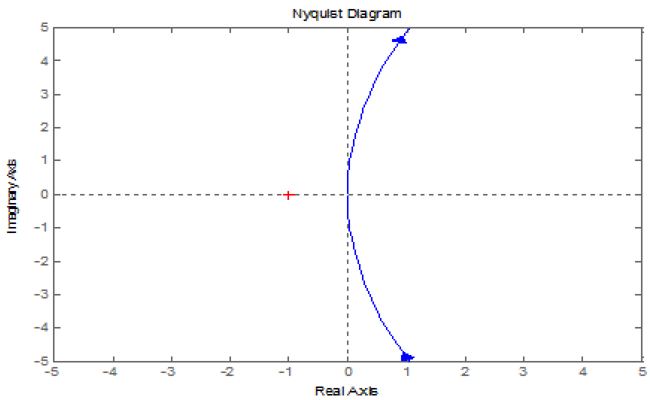

Figure 12: Nyquist Diagrams

3.3.2 Result Bode Plots

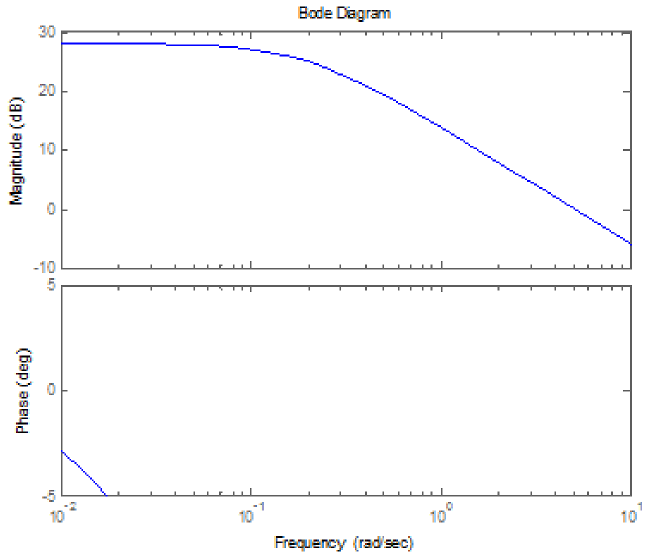

Figure 13: Body plots

From the previous results obtained that our system is stable.

4. Discussions

The control analysis and stability investigation of the crude distillation unit (CDU) in Khartoum refinery initiated by the modeling of the condenser, feed plate and the reboiler. The modeling equation were developed for each system and the transfer function for each were developed. Roots locus, Nyquist criterion and Bode technique were used to check the stability of the systems. Figures (5) illustrates the roots location for the Z—plane lies in the left side which indicates the system is stable for the re-boiler. In figure 8 indicates the system is stable for the condenser. Figure 11 shows the roots in left side which indicates the system is stable.

5. Recommendations

To avoid disturbance of the flooding for the flow rate is depend on difference pressure (Δp) in tower**,** when increased over proper level and to be high than the flow so cascade control should be used.

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