

Effect of reflux ratio on the design of distillation column of a bioethanol plant using cassava as feedstock

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ABSTRACT

Fuel ethanol research development deals with process design integration for improving production of ethanol. This paper investigates the effect of variable reflux ratio on the design of distillation column using developed JAVA based simulation software. This was done by varying reflux ratio as an input parameter and observed the effect it has on the number of trays that produced the column height. Varying reflux ratio arbitrarily from 3.094 to 9.301 produced column height ranging between 5.897 and 6.232 respectively. With the feed composition of ethanol-water mixture set at 45 percent, and the minimum reflux ratio of 3.4. The results showed that the number of trays decreases with increase in reflux ratio while the column height varies inversely with the reflux ratio.

Keywords: Fuel ethanol, Reflux Ratio, Simulation, Distillation Column. Process design

INTRODUCTION

The need for alternative energy has been on sharp increase in the recent past. This is due to increased instability in energy supply from oil producing regions of the world and the environmental impact associated with use of fossil fuel as energy source. It has therefore become necessary to source for alternative energy which is environmentally friendly, sustainable as well as reliable. One of such alternative energy source is the use of biofuels, which includes bioethanol (Ibrahim et.al, 2004, Umar et.al 2006 and Gupta et.al 2007). Bioethanol is an alcohol made by fermenting the sugar components of plant materials and it is made mostly from sugar and starch crops such as sugarcane, corn, beet, cassava, wheat and sorghum. With advanced technology being developed, cellulosic biomass, such as trees and

grasses, are also used as feedstocks for ethanol production. Ethanol can be used as a fuel for vehicles in its pure form, but it is usually used as a gasoline additive to increase octane and improve vehicle emissions. Fuel grade ethanol can wholly replace petroleum in modified vehicles (Wahoho 2007, Yamaji et. al, 2006). Cassava (*Manihot esculenta*) is an excellent source of ethanol due to its high starch content. It is the most popular root crop in Sub-Sahara Africa. Oyewole *et al.*, 2007 noted that the increasing potential of cassava as an individual crop has influenced the policy of the Federal Government of Nigeria in 2004 to embark on cassava multiplication program intended to supply fresh cassava roots and its product for the small and medium scale industrial uses and for exportation. To produce the bioethanol, it is necessary to separate ethanol from ethanol-water mixture after fermentation of alcohol. In practice, distillation is widely used for the separation (Seader and Henley, 1998) of this mixture therefore the distillation unit has to be design properly to enhance high purification. High purity of ethanol is required for efficient and effective utilization as gasoline fuel. Mechanical design of a distillation column of a bioethanol plant requires rigorous simulation of the process design for optimum parameters of which reflux ratio is of important. Industrial towers use reflux to achieve a more complete separation of products. Reflux refers to the portion of the condensed overhead liquid product from a distillation or fractionation tower that is returned to the upper part of the tower. Inside the tower, the downflowing reflux liquid provides cooling and condensation of the upflowing vapors thereby increasing the efficiency of the distillation tower. In existing designs, much has not been found in the literature on the effect of reflux ratio on the design of distillation column for bioethanol plant using cassava as feedstock. The purpose of this study is to investigate the effect of reflux ratio on the design of the distillation column of a bioethanol plant using cassava as feedstock.

THEORY OF DESIGN

Distillation Columns

Distillation columns are made up of several components, each of which is used either to transfer heat energy or enhance material transfer. A typical distillation unit contains the following major components:

- i. A vertical Shell where the separation of liquid is carried out.
- ii. Column internals such as trays/plates and /or packing which are used to enhance component separations.
- iii. A reboiler to provide the necessary vaporization for the distillation process.
- iv. A condenser to cool and condense the vapour leaving the top of the column.

v. A reflux drums to hold the condensed vapour from the top of the column so that liquid (reflux) can be recycled back to the column.

The vertical shell houses the column internals and together with the condenser and reboiler, constitutes a distillation unit as shown in Figure 1. Also, the distillation column is divided into three sections (Rectifying, Stripping and feed) as shown in Figure 2:

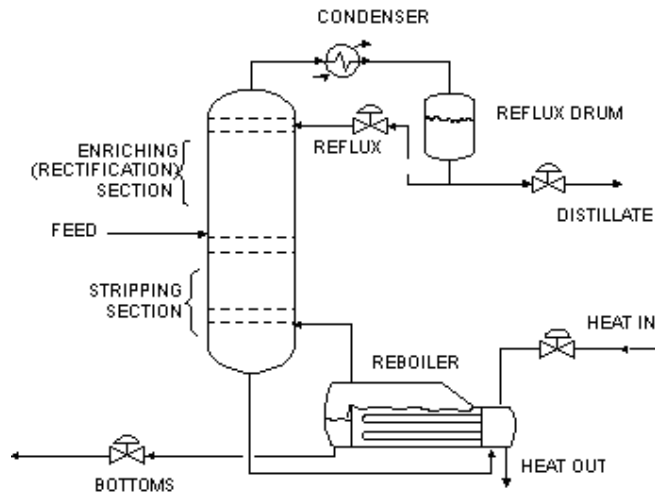
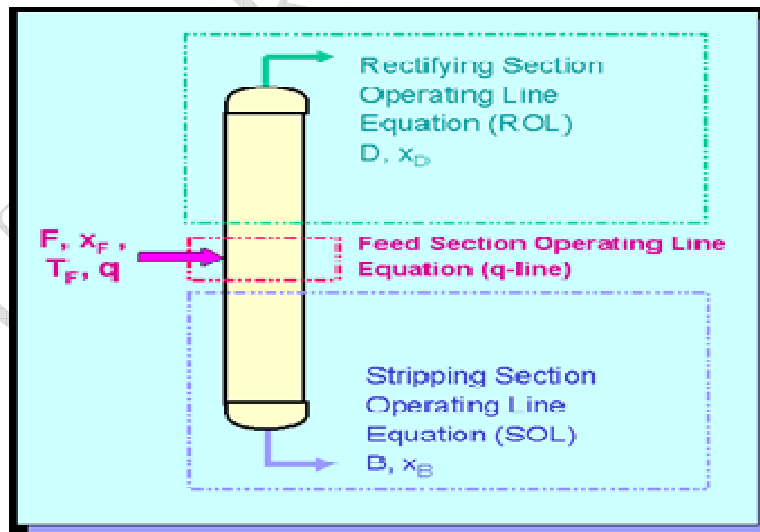


Figure 1. Main Components of Distillation Unit



85 Figure 2. Schematic diagram of distillation column showing the three major sections

86

87 Calculation for continuous binary distillation is given by Equation (1)

88
$$F x_F = B x_B + D x_D \quad (1)$$

89 Where; F, D, B are flowrates (kg.mol/hr) of feed, distillate, and waste or bottom, respectively.

90 x_F , x_D , x_B are mole ratios of the most volatile components in feed, distillate, and the bottom

91 respectively.

92 **Operation line**

93 Given x_n and L_n as the mole ratio and flowrate of the liquid phase flowing out of tray number
94 n, counting from the overhead, and given y_{n+1} and V_{n+1} as component and flowrate of vapour
95 rising up from tray number n+1, the operation line of the rectifying section (particular point
96 where location is above the feed point) can be drawn.

97

98 **Rectifying Section Operating Line (ROL)**

99 Considering the rectifying section shown in the Figure 2, the Material balance around the
100 envelope:

101 Material IN = Material OUT

102 Material balance in the distillation column

103 Overall Balance (Total): $V_{n+1} = L_n + D$

104 Component Balance (MVC): $V_{n+1} y_{n+1} = L_n x_n + D x_D$

105 Thus, we have

106
$$(L_n + D) y_{n+1} = L_n x_n + D x_D$$

107 Under constant molal overflow assumption:

108
$$L_1 = L_2 = \dots\dots\dots L_{n-1} = L_n = L_{n+1} = L = \text{constant}$$

109
$$V_1 = V_2 = \dots\dots\dots V_{n-1} = V_n = V_{n+1} = V = \text{constant}$$

110 The subscripts can be dropped. Thus, the equation simplifies to:

111
$$(L + D) y_{n+1} = L x_n + D x_D$$

112

113

114 Re-arranging in the form $y = f(x)$, we have

115
$$y_{n+1} = \left(\frac{L}{L+D} \right) x_n + \left(\frac{D}{L+D} \right) x_D$$

116 Where Reflux Ratio, $R = L / D$, then

117
$$y_{n+1} = \frac{R}{(R+1)} x_n + \frac{1}{(R+1)} x_D \quad (2)$$

118 This is the Operating Line Equation for the rectifying section or ROL

119 Usually the subscripts "n+1" and "n" are not shown, so that Equation 2 can be re written as:

120
$$y = \frac{R}{(R+1)} x + \frac{1}{(R+1)} x_D \quad (3)$$

121

122 **Feed Section Operating Line (q-line)**

123 Figure 3 shows the operating line for a feed tray considering the F moles/hr of feed, with

124 fraction q of liquid; thus liquid flow = $q F$ moles/hr and vapour flow = $(1-q) F$ moles/hr

125 Overall material balance:

126
$$L' = L + q F$$

127
$$V = V' + (1-q) F$$

128 Component balance for the more volatile component is as shown in Figure 4, thus,

129 Rectifying section: $V y = L x + D x_D$

130 Stripping section: $V' y = L' x - B x_B$

131 At the feed point where the two lines operating lines intersect:

132
$$(V - V') y = (L - L') x + D x_D + B x_B$$

133 we have:
$$V - V' = (1 - q) F$$

134
$$L - L' = - q F$$

135 In addition, from component balance around the entire column:

$$F x_F = D x_D + B x_B$$

Thus, $(1 - q) F y = -q F x + F x_F$

Re-arranging in the form $y = f(x)$, we have:

$$y = -\frac{q}{(1+q)} x + \frac{1}{(1-q)} x_F \quad (4)$$

For a given feed condition, x_F and q are fixed; therefore the q -line is a straight line with slope $-q / (1-q)$ and intercept $x_F / (1-q)$.

If $x = x_F$, then $y = x_F$.

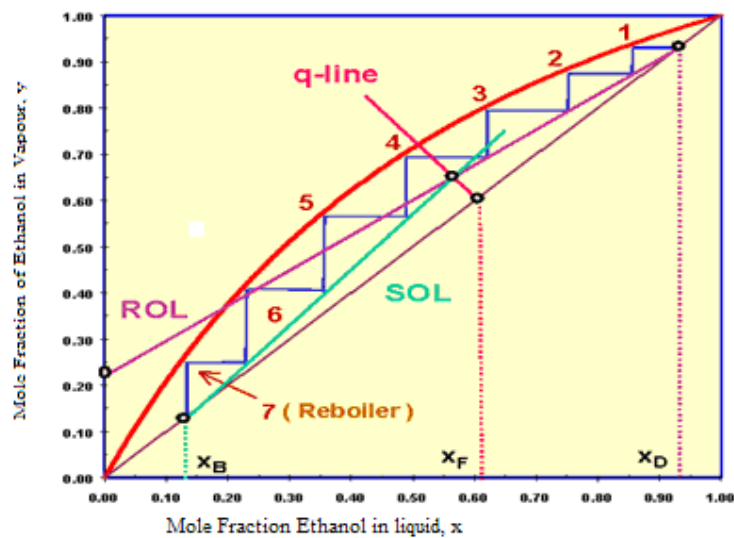


Figure 3 Equilibrium curve for the binary mixture

144

145

146 Analysis of Stripping Section

147 Analysis of SOL is presented below using the Figure 2 which shows the stripping section of a
 148 distillation column. The reboiled vapour in equilibrium with bottoms liquid leaving the
 149 column.

150 Material balance: Mass IN = Mass OUT

151 Assuming constant molar overflow

152 $L'_m = L'_{m+1} = \dots = L' = \text{constant}$

153 $V'_m = V'_{m+1} = \dots = V' = \text{constant}$

154 Material balance:

155 Overall : $L' = V' + B$

156 MVC : $L' x_m = V' y_{m+1} + B x_B$

157 Substituting, and re-arrange in the form $y = f(x)$, we obtain

158 $y_{m+1} = \left(\frac{L'}{V'} \right) x_m - \left(\frac{B}{V'} \right) x_B$

159 Again, dropping the subscripts "m+1" and "m" we have:

160 $y = \left(\frac{L'}{V'} \right) x - \left(\frac{B}{V'} \right) x_B$

161 Substituting $V' = L' - B$: we have the stripping operating line (SOL)

162 $y = \frac{L'}{(L'-B)} x - \frac{B}{(L'-B)} x_B$ (5)

163 This is straight line with slope $(L' / L' - B)$ and intercept $(B x_B / L' - B)$

164

165 **Determination of Number of Trays**

166 The Fenske Equation (Fenske, 1932) was used for determining the minimum number of trays
167 required for a given separation. It is an example of a "shortcut" distillation method.

168

169
$$N_{\min} = \frac{\ln \left(\frac{x_D(1-x_B)}{x_B(1-x_D)} \right)}{\ln(\alpha_{AB})}$$
 (6)

170 The Fenske equation when applied to distillation systems assumes constant Relative
171 Volatility (RV).

172 **Minimum Reflux ratio**

173 The minimum reflux ratio is determined mathematically from the endpoints of the rectifying
174 line at minimum reflux ratio using Equation 7. The overhead product composition point (x_D ,
175 x_D) and the point of intersection of the feed line and equilibrium curve (x' , y') are as shown in
176 Figure 4.

$$R_{\min} = \frac{x_D - y'}{y' - x'} \quad (7)$$

Theoretical number of trays was determined using Equation (8) by Gilliland (1993)

$$N - N_{\min} / N + 1 = 0.75 \left[1 - \left(R - R_{\min} / R + 1 \right)^{0.566} \right] \quad (8)$$

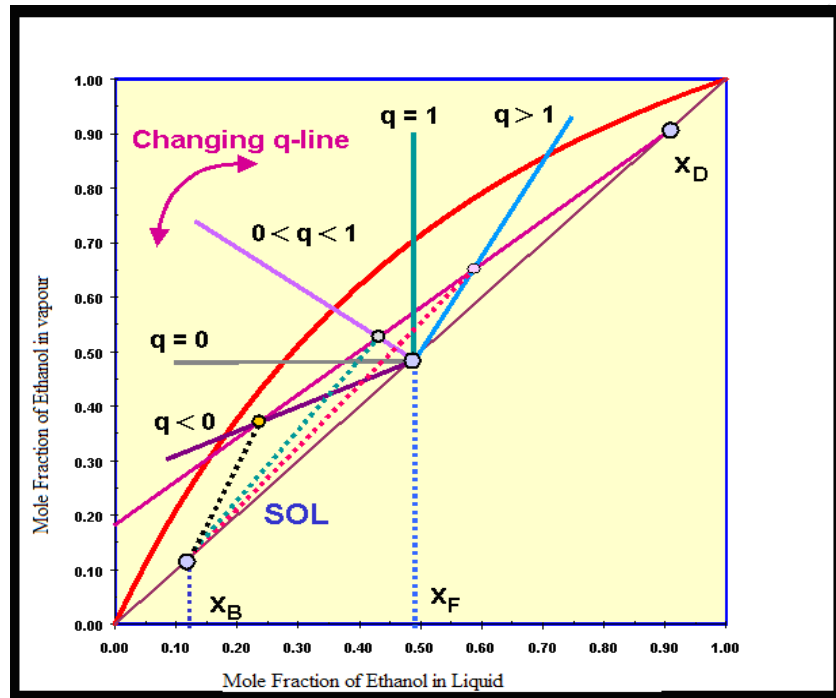


Figure 4 shows 3 different SOL that correspond to 3 different q-lines, for a given ROL (i.e. fixed R and x_D).

PROCESS SIMULATION

Process simulation is a model-based representation of chemical, physical, biological, energy producing and transforming, in addition to other technical processes and unit operations using software. The software has to solve the mass and energy balances, and find a stable operating point with optimal conditions for the process examined. Process simulation always uses models which introduce approximations and assumptions, but allow the description of a

property over a wide range of parameters which may not be covered by real data. Models also allow to interpolate or extrapolate, searching for conditions outside the range of known properties.

MATERIALS AND METHODS

The process design software used for this work was developed using JAVA programming language hinged on McCabe-Thiele graphical method and Fenske equations to determine theoretical and actual number of stages involved in the distillation process.

The process design parameters such as Reflux Ratio (R), Coefficient of Reflux (R_{Coeff}), mole fraction of the most volatile component in distillate (x_D), mole fraction of the most volatile component in bottom (x_B), mole fraction of the most volatile component in feed (x_F), Viscosity, thermodynamic property of feed (q) were simulated for optimum values through parametric process. Reflux ratio was then varied to give the mechanical design parameters (Number of trays and column height). The screen shot of the designed software is shown in Figure 5.

A central composite experimental design was used to test the design software by varying the design parameters at five levels each. The design allows the fixing of the lower and upper limits for each of the parameter tested. The parameters are R , RV , x_D , x_B , x_F while responses were Theoretical number of Trays in column (NT); Fenske Number of Trays; Mc-Cabe Number of Trays, Column height and the Efficiency of distillation column

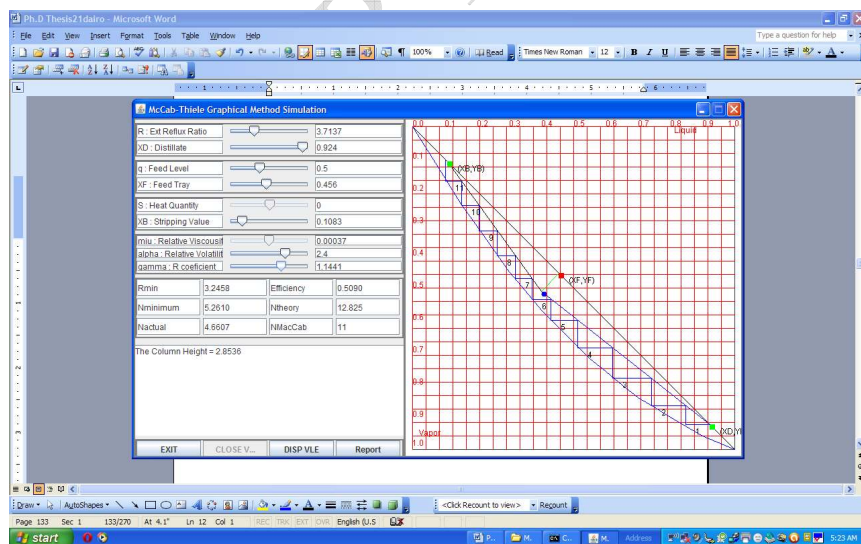


Figure 5. A screen shot of a typical run of the design software

RESULTS AND DISCUSSIONS

Figures 6,7, and 8 show the input and output results of the effect of reflux ratio on number of trays when the values of reflux ratio is 3.094, 3.713, and 4.180 respectively determined by the developed software at constant relative volatility. The same procedure was repeated for the values of reflux ratio of 5.733, 6.274, 6.819, 7.439, 7.984, 8.447, and 9.30 with the generated output shown in Table 1. The values shown in Table 1 were plotted to produce Figures 9 and 10 which show the effect of reflux ratio on number of trays and column height respectively.

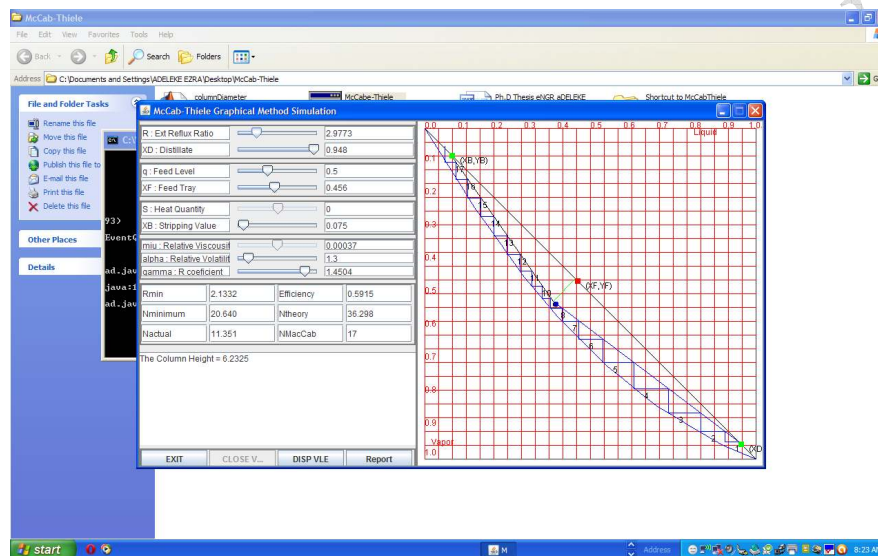


Figure 6. Report of McCabe-Thiele graphical simulation of a distillation column at $R=3.094$

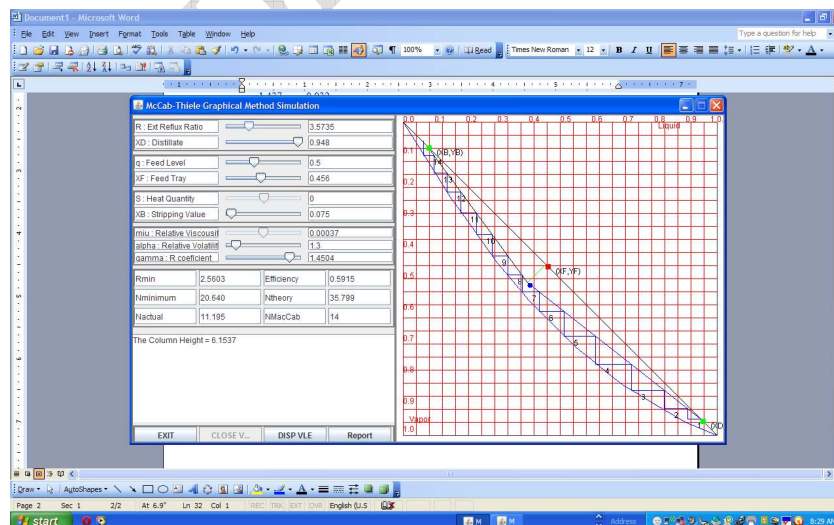


Figure 7. Report of McCabe-Thiele graphical simulation of a distillation column at $R=3.713$

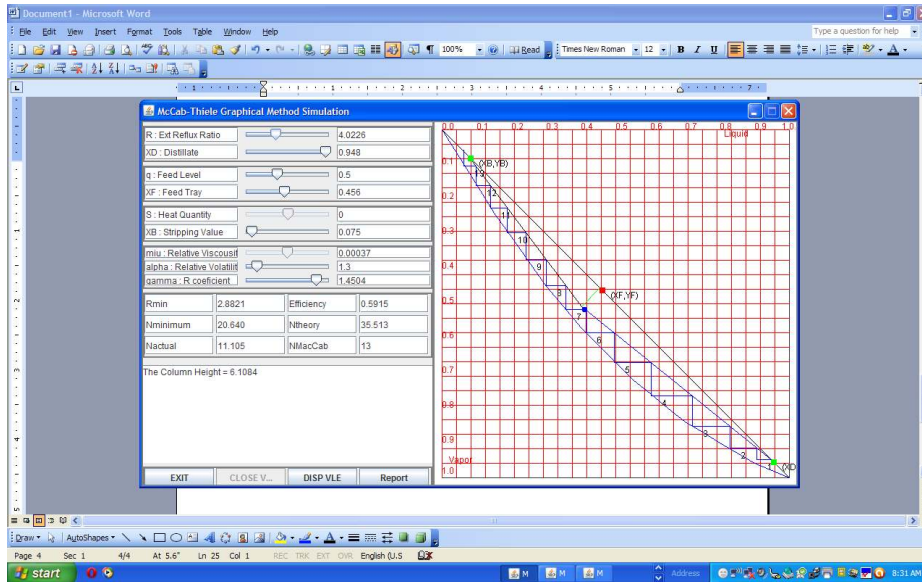
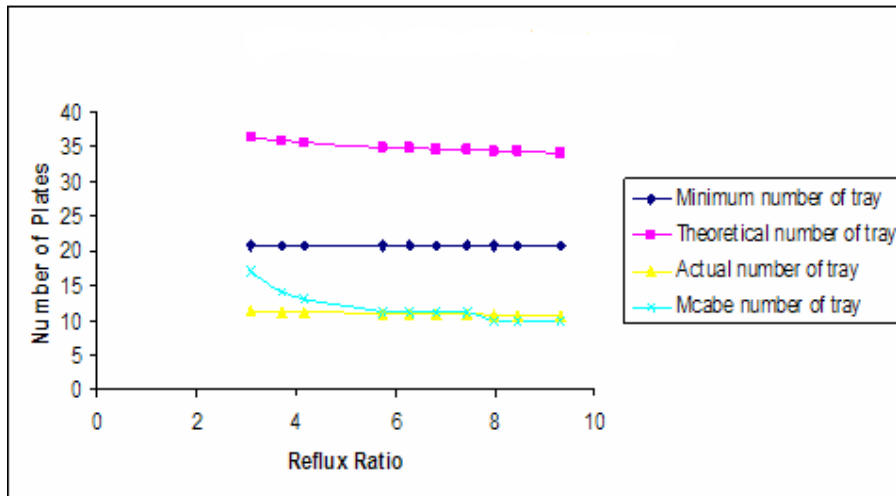


Figure 8. Report of McCabe-Thiele graphical simulation of a distillation column at $R=4.180$

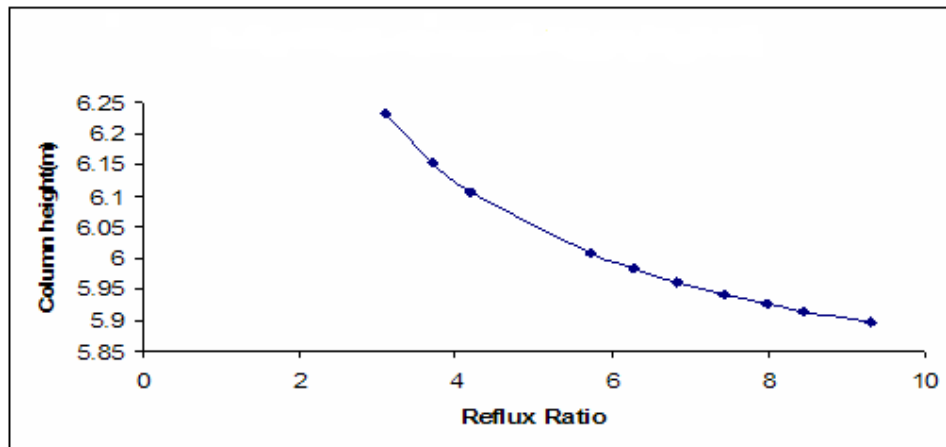
Table 1 Effect of Reflux Ratio on the Theoretical Number of Tray at Constant RV

Reflux Ratio	Minimum number of tray	Theoretical number of tray	Actual number of tray	McCabe number of tray	Column height(m)
3.094	20.64	36.29	11.35	17.0	6.232
3.713	20.64	35.79	11.19	14.0	6.153
4.180	20.64	35.51	11.10	13.0	6.108
5.733	20.64	34.87	10.90	11.0	6.007
6.274	20.64	34.71	10.85	11.0	5.983
6.819	20.64	34.58	10.81	11.0	5.962
7.439	20.64	34.46	10.77	11.0	5.942
7.984	20.64	34.36	10.74	10.0	5.927
8.447	20.64	34.29	10.72	10.0	5.915
9.301	20.64	34.17	10.62	10.0	5.897



249

250 Figure 9. Effect of Reflux Ratio on number of plates



251

252 Figure 10. Effect of Reflux Ratio on distillation column height

253

254

255 The test results of the experiment showed that reflux ratio has a negative effect on the number
 256 of trays using the developed software as shown in Figure 10; an increase in reflux ratio
 257 produced a reduction in number of trays and consequently the column height. This is not
 258 unexpected as using a higher reflux ratio results in less number of trays required. Adelekan
 259 (2010) in a research on ethanol productivity from cassava reported a similar observation in his
 260 study. A column with a high R may have fewer stages, but it refluxes a large amount of liquid,
 261 giving a wide column with a large holdup. Conversely, a column with a low R must have a
 262 large number of stages, thus requiring a taller column (Toliver and McCume, 1978, Roat
 263 et.al., 1988) this is evident in Figure 10.

264

265 **Conclusion**

266 The Reflux Ratio (R) had a negative effect on the no of trays using both the Mc-Cabe and
267 Fenske equations; an increase in R produced a reduction in number of trays and consequently
268 the column height.

269

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