THERMO-ECONOMIC ANALYSIS OF SEPARATION OF BENZENE-TOLUENE-XYLENE SYSTEM USING MODIFIED DESIGN OF DIVIDED WALL COLUMN

Abstract

The ongoing is the age of process intensification, wherein the best and most cost-efficient ways are chosen to revamp the conventional methods or equipments. Distillation is an age-old process but to make it run with modern day processes it has been modified in several ways, within the column as well as in the process. Here, in this research work, we have considered a three-feedmixture, commonly known as BTX system being separated in a partitioned wall column. The paper incorporates the modified and detailed design equations based on conventional multicomponent design equation FUGK, along with DWC design correlations given by Murlikrishna and Sotudeh with relevant changes to ease the steps involved in designing. The design module has been considered and is compared with conventional sequential columns for their techno-economic feasibility. Also, a modification is proposed for a more consistent middle product, which is usually an issue while running such columns and the same has also been accounted for energy calculations and economic benefits.

Keywords: Divided Wall Distillation Column, Side stream consistency, Design Algorithm, MATLAB®, MSCM

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I. INTRODUCTION

Multi component distillation refers to separation of many components via simultaneous evaporation and condensation. Therefore, for separation of n components, (n-1) distillation columns are required, along with respective accessories like reboilers and condensers [1].In order to save capital cost, operating cost, floor space and need of auxiliaries it is preferred to use integrated column. One way of integrating distillation columns is to employ fully thermally coupled distillation columns, proposed by Petlyuk[2]. the other way is applying divided wall columns (DWC), designed by Kaibel[3]. Kaibel's model has unique advantage over Petlyuk's model i.e. large energy as well as fixed cost savings occur because of use of single column for distillation, along with only one reboiler and one condenser as compared to that of conventional arrangement. This is because of the avoidance of remixing of internal streams, which in two columns in series arrangements exhibit concentration peaks of middle boiling component either above or below the feed. Additional benefit comes from the fact that the prefractionator arrangement, which distributes the intermediate component between the top and bottom, allows greater freedom to match the feed composition with a tray in column to further reduce the mixing losses at the feed tray[4]. The mixing as well as remixing of streams with different compositions that occurs at the feed point(s) and along column, which inevitably accompanied by entropy of mixing formations, is an intrinsic source of thermodynamic inefficiency of separation process occurring in multicomponent distillation column[2]'[5]'[6]. Theoretical studies have shown that it can save up to 30% of energy costs compared to that of conventional arrangements[7]. From the point of mathematical modelling, a DWC is practically identical to a Petlyuk Column, if the heat transfer across the column wall is neglected or the wall is well insulated [5,8].

Partitioned Wall Columns or Dividing Wall Columns are no newer, they have been working in industries since early 70s. The only barrier to its popularization and commercialization is the unavailability of proper set of design equations in literature. Although, the basics of the dividing wall column has already been discussed in several books and research papers [9,10].

By far a number of models have been published in literature dealing with the design of Dividing Wall Column. Triantafyllou and Smith, published a first design oriented short cut method for a 3-product based on so called FUGK model, a well known combination of individual models to establish the minimum number of equilibrium stages (Fenskey), minimum reflux (Underwood), stage required at chosen operating reflux ratio (Gilliland), and the feed stage (Kirkbride) for a given separation. Basic assumptions of this model area are constant relative volatility and constant molar flows[1,11].

Similar shortcut method was used by Murlikrishna et al., who proposed a useful visualization tool to represent all feasible designs on a single plot, which can also be utilized for a simple optimization technique[10,12].

Amminudin et al. pointed out that the use of Kirkbride equation, to find thermal coupling locations can lead to errors when transferred to rigorous simulation. They produced a semi-rigorous design method based on equilibrium stage composition concept. Their design procedure starts from defined products composition and works backward to determine design parameters to achieve them. The authors claim that their method provides more accurate base-case design than the standard FUGK based shortcut methods. However, their method is computationally more demanding. Literature shows that the method initially developed by Triantafyllou and Smith is preferred because of its simplicity[10,13–15].

Sotudeh et al. proposed a method for design of three component feed divided wall distillation column based on Underwood equations, as they consider the use of Fenskey equation for minimum number of stages is inadequate for application in DWC design. This is due to the fact that the Fenskey equation is based on assumption of equal compositions of liquid and vapor streams at top and bottom of prefractionator column, which is clearly not in case of DWC. In the method, the minimum vapor flow and minimum reflux ratio in the column are determined. Followed by choosing an operating reflux ratio in the range of 1.2–1.5 R_{min}; the total number of trays in the tower and the side stream location are calculated. According to case study presented in their paper, their method proves to be more economical DWC design compared to the method of Murlikrishna et al [1,10,15,16].

II. DESIGN

The design methodology used here is based on the model developed by Sotudeh and Shahraki (2007) for vapour flow calculation. While they have used only Underwood's equation for rest of calculations, here the conventional FUGK method along with Murlikrishna's model has been considered. Despite the limitations of Fenskey's equation this model is well suited for rough design estimation. The system is restricted for three components in single feed system only. The proposed method incorporates both the design methods with following changes, and henceforth will be termed as Murlikrishna and Sotudeh Combined Modified (MSCM) method [1,12,16].

- The reflux has been taken as 10% more than the minimum reflux, equation 34. This value of reflux is lower than that of Sotudeh's Method, thereby, saving lot of operating cost.
- Minimum liquid flow rates in section 2 and 3 are given by equations 36-39. Use of these equations reduces the complexity and makes the calculation easier.
- The maximum amount of liquid flow at the top of the column and bottom of the section 2, as depicted by equations 35 and 42, helps in better design of the column.
- Simple Mass balance equations have been used for determining compositions of feed streams 2 and 3, as given in equation 45 and 46.
- Simple equations 48-49 have been used to estimate number of stages in rectifying and stripping sections.
- Consequently, equations 57 and 58 give the liquid and vapour recycle stages respectively.

Usage of these simple equations makes calculations easy and effortless, making the program more robust.

1. **Material Balance Equation:** From the figure 1, we have the following material balance equation[17].

$$\mathrm{Abalance: Fz_A = D_2x_{AD2} + Sx_{AS} + W_3x_{AW}} \quad (1)$$

$$\mathrm{Bbalance: Fz_B = D_2x_{BD2} + Sx_{BS} + W_3x_{BW}} \quad (2)$$

$$\mathrm{Cbalance: Fz_C = D_2x_{CD2} + Sx_{CS} + W_3x_{CW}} \quad (3)$$

$$x_{AD2} + x_{BD} + x_{CD2} = 1 ---------- (4)$$

$$x_{AS} + x_{BS} + x_{CS} = 1 ------------ (5)$$

$$x_{AW3} + x_{BW} + x_{CW} = 1 ---------(6)$$

2. **Minimum Vapor Flow Calculations**[1]**:** As seen from Fig. 1, the column in the current model has been divided into three different sections, 1, 2 and 3. The minimum vapor flow and pinch condition could occur in any of these sections. The choice of the highest value of the minimum vapor flow would ensure that the required separation of the components across each section of the column could be achieved simultaneously. Any smaller value of the minimum vapor flow might lead to inconsistencies, as described by Yaws [18].

   From the above equations, it is seen that there are twelve unknowns, while the known parameters are the feed rate and its compositions. Therefore, in order to solve the above equations, six of the unknowns must be specified. The specified parameters are suggested to be $x_{AW3}, x_{CW3}, x_{AD2}, x_{CD2}, x_{BS}$ and $\frac{x_{AS}}{x_{CS}}$.

   - **Section 1:** Consider that a saturated feed of compositions z_A, z_B, and z_C, and quality q, (0 <q < 1) is fed to section 1. The relative volatilities of A, B and C with respect to C are assumed to be constant and equal to α_A, α_B and α_C, respectively. Therefore, the fractional recovery of component i in the top product can be defined as:

$$r_{i,T} = \frac{x_{iD1}D_1}{z_iF} ---------------(7)$$

   Here D_1 is the net stream flowing through to the top of section 1.
   Thus one can represent the top component compositions in terms of their recoveries, as specified below:

$$r_{A,T} = 1;\ r_{B,T} = \beta;\ r_{C,T} = 0 ---------(8)$$

$$x_{A,D1} = \frac{Fz_A}{D_1}\ ;\ x_{B,D1} = \beta\frac{Fz_B}{D_1}\ ;\ x_{A,D1} = 0;\ -(9)$$

$$D_1 = z_AF + \beta z_BF ------------ (10)$$

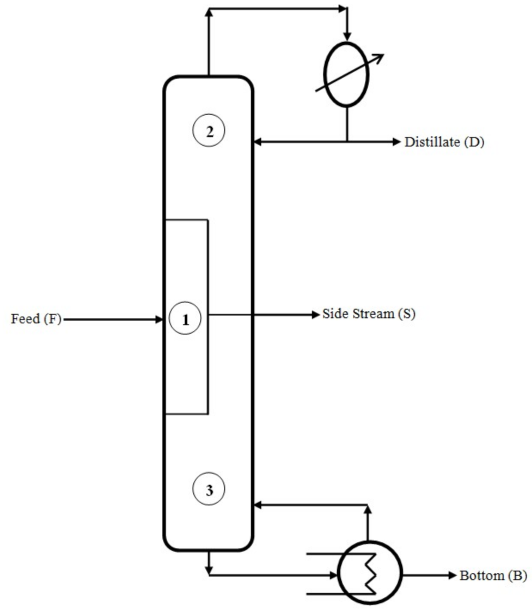

Figure 1: Divided Wall Column Schematic Diagram

Similarly for the net stream flowing to the bottom of section 1, one can write:

$$r_{i,B} = \frac{x_{iW1}W_1}{z_iF} \text{--------------} (11)$$

$$r_{A,B} = 0;\ r_{B,B} = 1-\beta;\ r_{C,B} = 1; \text{-----}(12)$$

$$r_{AW1} = 0;\ r_{BW1} = (1-\beta)\frac{Fz_B}{W_1};\ r_{CW} = \frac{Fz_C}{W_1} (13)$$

$$W_1 = z_BF(1-\beta) + Fz_C \text{---------}(14)$$

Using Underwood's equation at the minimum reflux condition:

$$F(1-q) = \sum \frac{\alpha_i z_i}{\alpha_i - \theta} \text{----------} (15)$$

$$V_{min,1} = \sum \frac{\alpha_i x_{i,D} D_1}{\alpha_i - \theta} \text{-----------}(16)$$

Combining equation (8) and (16):

$$V_{min,1} = \frac{\alpha_A Z_A F}{\alpha_A - \theta} + \beta\frac{\alpha_B Z_B F}{\alpha_B - \theta} \text{------}(17)$$

Solving Eq. (15) for its roots, results in three values being found for θ. Inspection of these values shows that one of them is negative and should be rejected. The remaining two roots are in the following ranges:

$$\alpha_A > \theta_1 > \alpha_B > \theta_2 > \alpha_C \text{------------} (18)$$

V_{min1} is calculated based on the accepted roots and is chosen to be:

$V_{min1} = Max\{ V_{min1}(\theta_1), V_{min1}(\theta_2)\}$ - - - - - - - - - (19)

Both V_{min1} (θ_1) and V_{min1} (θ_2) change with β. The value of β at which V_{min1} (θ_1) = V_{min1} (θ_2) is called the preferred split and from work by Stichlmair, is denoted by βp. βp is given as:

$$\beta p = \frac{\left(\frac{\alpha_A * FZ_A}{\alpha_A - \theta_1}\right) - \left(\frac{\alpha_A * FZ_A}{\alpha_A - \theta_2}\right)}{\left(\frac{\alpha_B * FZ_B}{\alpha_B - \theta_1}\right) - \left(\frac{\alpha_B * FZ_B}{\alpha_B - \theta_2}\right)} - - - - - (20)$$

The other flow streams inside section 1 are calculated by following relations:

$L_{min1} = V_{min1} - D_1$ - - - - - - - - - - - - - - - - - - -(21)
$\tilde{V}_{min1} = V_{min1} - (1\text{-}q)*F$ - - - - - - - - - - - - - - - - -(22)
$\bar{L}_{min1} = L_{min1} - qF$ - - - - - - - - - - - - - - - - - - - (23)

- **Section 2:** The net stream from the top of section 1 is fed to section 2, i.e., $F_2 = D_1$. The top stream product of section 2 is D_2. The compositions of this stream are $x_{i,D2}$. Therefore, at the minimum reflux condition:

$$q' = -\frac{L_{min1}}{D_1} - - - - - - - - - - - - - -(24)$$

$$F_2(1-q') = \sum \frac{\alpha_i x_{i,D1} F_2}{\alpha_i - \theta'} - - - - - - - - (25)$$

Here, i = {A, B} and $F_2 = D_1 = z_A F + \beta z_B F$

$$V_{min2} = \sum \frac{\alpha_i x_{i,D2} D_2}{\alpha_i - \theta'} - - - - - - - - - - - (26)$$

$$V_{min,1} = \frac{\alpha_A Z_A F}{\alpha_A - \theta'} + \beta \frac{\alpha_B Z_B F}{\alpha_B - \theta'} - - - - - - -(27)$$

Two values of θ' is obtained between the range of $\alpha_A > \theta' > \alpha_B$

$$q" = \frac{\bar{L}_{min1}}{W_1} - - - - - - - - - - - - - - - - -(28)$$

$$F_3(1-q") = \sum \frac{\alpha_i x_{i,W1} F_3}{\alpha_i - \theta"} - - - - - - -(29)$$

Here, i = {B, C} and $F_3 = W_1 = z_C F + (1\text{-}\beta) z_B F$

$$\tilde{V}_{min3} = \sum \frac{\alpha_i x_{i,W3} W_3}{\alpha_i - \theta"} - - - - - - - - - - - (30)$$

$$-\tilde{V}_{min,1} = \frac{\alpha_C Z_C F}{\alpha_C - \theta"} + (1-\beta)\frac{\alpha_B Z_B F}{\alpha_B - \theta"} --(31)$$

Two values of θ" is obtained between the range of $\alpha_B > \theta" > \alpha_C$

$V_{min2} = V_{min,petyluk} = \text{Max}\{V_{min2}, \tilde{V}_{min3}, (1-q)F\}$----(32)

3. **Reflux ratio and internal reflux:** Here, in this section the equations for reflux ratios and the liquid flow rates are calculated from the following set of equations.

$$R_{min} = \left(\frac{V_{min2}}{D_2}\right) - 1 -----------(33)$$

$R = 1.1*R_{min}$ - (34)
$L_2 = R*D_2$ - (35)
$L_{min2} = R_{min}*D_2$- (36)
$\bar{L}_{min2} = L_{min2} + (D_1*q_2)$ - - - - - - - - - - - - - - - - - (37)
$L_{min3} = \bar{L}_{min2}$-S - (38)
$\bar{L}_{min3} = -(W_1*q_3)+L_{min3}$ - - - - - - - - - - - - - - -(39)

Internal reflux r is given as:

$$r_m = \frac{\max\left(\frac{\bar{L}min2}{L2}, \frac{Lmin3+S}{L2}, \frac{L2-\bar{L}min1+qF}{L2}\right)}{2} --(40)$$

$r = 1.1*r_m$ - (41)
$\bar{L}_2 = L_2*r$ -(42)
$W_2 = \bar{L}_2+S$- (43)
$D_3 = W_2+S$- -(44)

$$x_{if2} = \frac{(D_2 * x_{iD2}) + (W_2 * x_{iS})}{D_1} ----- (45)$$

$$x_{if3} = \frac{(D_3 * x_{iS}) + (W_3 * x_{iW3})}{W_1} ----- (46)$$

4. **Number of Stages:** The minimum numbers of stages are calculated from the Fenskey Equation:

$$N_m = \frac{\left[\left(\frac{xLK}{xHK}\right)_d \left(\frac{xHK}{xLK}\right)_b\right]}{log\alpha_{LK}} ---------- (47)$$

$$N_{m1} = \frac{\left[\left(\frac{xAf2}{xCf2}\right)\left(\frac{xC}{xA}\right)\right]}{log\alpha_A} ---------- (48)$$

$$N_{m2} = \frac{\left[\left(\frac{xAd2}{xBd2}\right)\left(\frac{xBs}{xAs}\right)\right]}{log\alpha_A} -----------(49)$$

$$N_{m3} = \frac{\left[\left(\frac{xBs}{xCs}\right)\left(\frac{xCw}{xBw3}\right)\right]}{log\alpha_B} ---------- (50)$$

For actual number of trays, Gilliland's Correlations with Eduljee's equations are used:

$$y = 0.75(1 - x^{0.5668}) ---------- (51)$$

Here,

$$x = \frac{R - Rm}{R + 1} -------------- (52)$$

$$N = \frac{y + Nm}{1 - y} -------------- (53)$$

Here, for 1st section:
$R = R$;
$R_m = R_m$;
$N_m = N_{m1}$
For 2nd section:
$R = r$;
$R_m = r_m$;
$N_m = N_{m2}$
For 3rd section:
$R = r$;
$R_m = r_m$;
$N_m = N_{m3}$

Therefore, total number of trays in Petyluk's column will be $N = N_2+N_3$
The feed tray location is determined by Kirkbride's Equation:

$$log\left(\frac{N_{r1}}{N_{s1}}\right) = 0.206log\left[\left(\frac{W1}{D1}\right)\left(\frac{z_C F}{z_A F}\right)\left(\frac{x_{Af3}}{x_{Cf2}}\right)^2\right] ------------ (54)$$

The side stream stage is given as $N_2 + 1$.

$N_{r2} = N_2 – N_{r1}$ -------------------------------------- (55)
$N_{s2} = N_2 - N_{r2}$ -------------------------------------- (56)
$N_{r3} = N_3 - N_{s1}$ -------------------------------------- (56)
Liquid Recycle Stage = $N_{r2} + 1$ ----------------- (57)
Vapour Recycle Stage = $N_{r3} + 1$ ----------------- (58)

III. ALGORITHM

The program has been developed in MATLAB version R2017b. The program has checks at every data input, so that junk value entry can be restricted. The interactive GUI (Graphical User Interface) makes it simple to use and easy to understand and interpret the results. The module presented here is itself a combination of several other small and required modules which facilitates in tailor made system. The program module developed works on following algorithm (FIG. 2).

IV. CASE STUDY

To validate the model and the program, the same example suggested by Murlikrishna and subsequently taken by Sotudeh is considered, along with the following inputs (Table 1):[2,3]

Table 1: Case study details (Benzene – Toluene – Xylene)

Feed Compositions (A,B,C)	zf_i's = {0.333,0.333,0.334}
Molar Feed	F = 30 mol/hr
Relative Volatilities	α_i's = {6.773, 2.789, 1}
Feed Quality	q = 0.557
Outlet Specifications	$x_{AD2} = x_{CW3} = 0.95$
	$x_{BS} = 0.9$
	$x_{BD2} = x_{BW3} = 0.05$
	$x_{AS}/x_{CS} = 1$

V. DISCUSSION FOR DESIGN

A robust model for design of DWC is presented along with coding using MATLAB software. The design model is based on Murlikrishna and Sotudeh model with necessary changes. The model is validated using a three feed multi-component system from literature. This model gives better result as compared to both the individual models.

When we compare the MSCM model with the original models, some differences are observed (Table 2). In case of, $V_{min,pet}$ the minimum vapour flow that should be taken as highest value among all the minimum vapour flow rates obtained in different section, here that value seems to be higher than that of previous models, thus the later can be said to be under-designed. Secondly, the number of trays in section 1 comes to almost half from Murlikrishna's model and also 2 less than Sotudeh's model, thus reducing the extra plates that may not be needed. This is also justified by the fact that feed tray location turns up to be same as Sotudeh's model. Also, number of trays in section 2,3 comes same as that of Murlikrishna's model and justifies well as maximum separation takes place here only. The vapour recycle stage comes to 12, thus providing a more consistent quality of product C; here it should be noted by the same method liquid recycle stage is same that is one can say previous models were more focused on top product quality. There is no much difference in reflux ratio R2 i.e. there won't be significant change in reboiler duty and condenser duty. The change in internal reflux ratio can account for varying quality of component B in side stream.

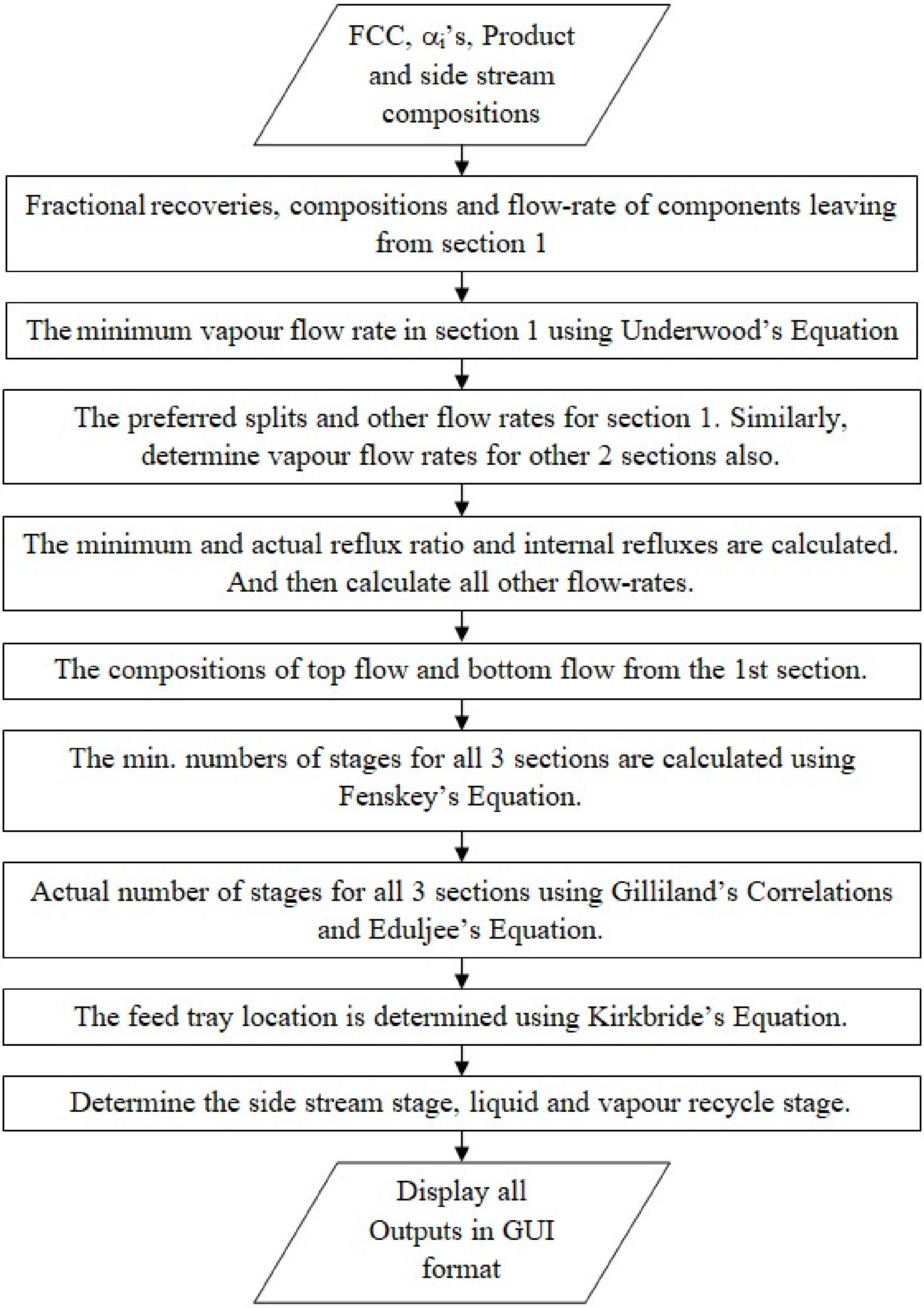

Figure 2: Algorithm for Proposed Model

It is also evident from the design steps used that this method is simple as it do not require any plotting of graphs, solving complex equations or having cumbersome calculations. DWC is being increasingly considered for multi-component distillation. The proposed design can be used for rough design estimation as it incorporates all the pre-defined assumptions of methods adopted.

Table 2: Comparison of Results with the two methods

Methods	**Number of trays in section 1**	**Feed Stage**	**Number of trays in section 2,3**	**Liquid Recycle Stage**	**Vapour Recycle Stage**	**Side Stream Stage**	R_2	**Internal Reflux r**	$V_{min,petyluk}$
Murlikrishna	12	10	25	6	19	12	3.46	-	
Sotudeh Preferred Splits	8	4	16	5	13	10	3.46	0.73	31.95
Sotudeh Balanced Splits	8	4	17	6	14	11	3.46	0.69	31.95
MSCM Model	6	4	24	6	12	10	3.59	0.55	42.65

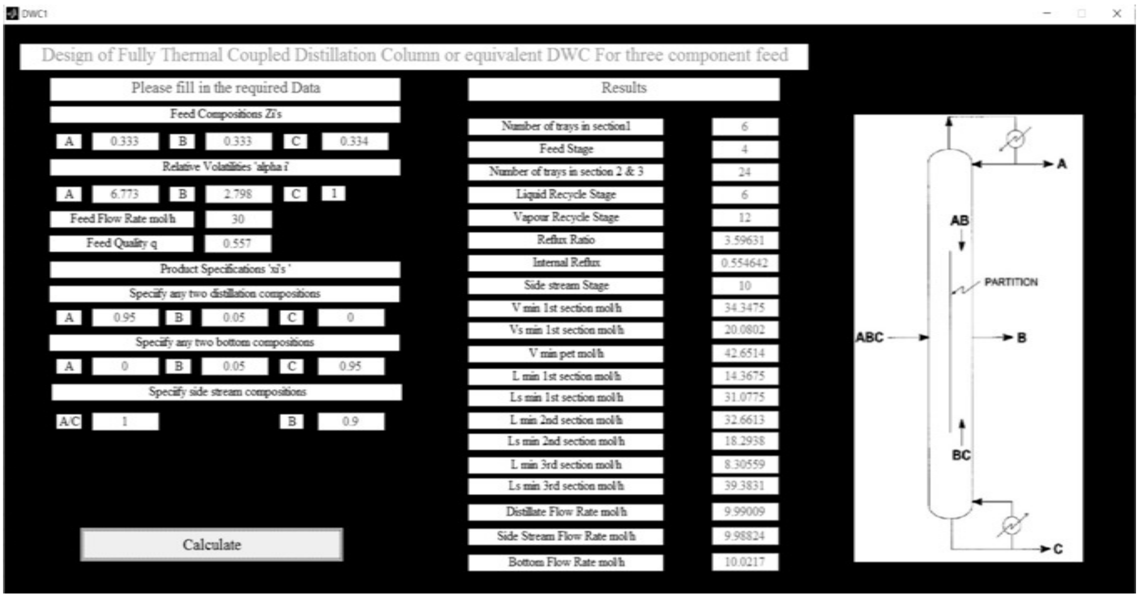

Figure 3: Output window of program run for corresponding case study

VI. MODIFICATION FOR CONSISTENT SIDE PRODUCT

The change in internal reflux ratio can account for varying quality of component B in side stream. In case, if user wishes to have composition of component B to be consistent then the user can go for one reboiler or one condenser even at the outlet of side stream. This may seem to increase the operating cost but that will still be lower than operating two distillation columns in sequences, or having multiple numbers of reboilers and condensers in single column. In addition, the improved and consistent product quality will overcome the expenses incurred. The proposed idea is represented by schematic diagram (FIG. 3) below.

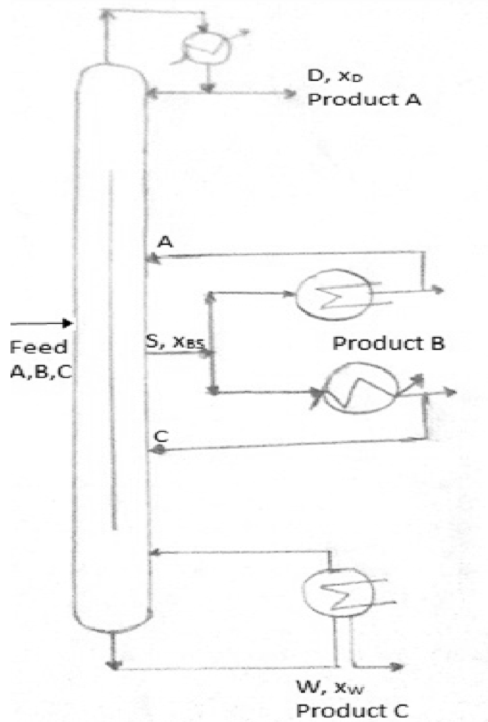

Figure 4: Proposed DWC Model

VII. COMPARISON OF HEAT DUTY REQUIRED

1. **Direct Sequence of two columns:** This is the usual arrangement for separating three components system in industry conventionally. The arrangement is in correspondence to the fact that separation of n components in multi-component distillation requires (n-1) columns. The feed and the product specifications are same as that given in table 1.

   Here, we have two columns each having a condenser and a reboiler.
   For column 1, the feed temperature is given as 100 ºC with feed being a liquid – vapour mixture. Column 1 will separate Benzene from the other two components. Calculation of dew point gives the top temperature as 82.5 ºC and the bubble point calculations give the bottom temperature as 124.3 ºC. Heat available with the feed is calculated to be 11.93 kW whereas heat duty of condenser is nearly 413.2 kW and reboiler load is 456.48 kW.

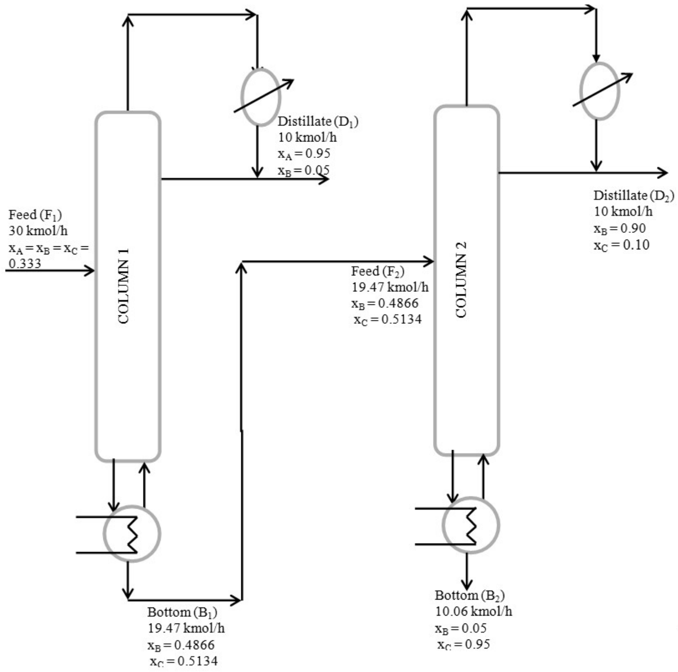

Figure 5: Flow Diagram for Direct Sequencing of Columns

Table 3: Energy Calculation summary for Column1 in conventional sequence columns

For Column 1	
Top Temp.	82.5 ºC
Heat Duty of Condenser 1	413.116 kW
Feed Temperature	100 ºC
Heat in Feed (F*q*H_F)	11.93 kW
Bottom Temp.	124.3 ºC
Heat in Residue	33.561 kW
Heat Duty of Reboiler 1 (5% loss)	456.48 kW

In column 2, we have negligible Benzene whereas we need a sharp separation between Toluene and o-Xylene. The bottom product of the first column is feed to the 2nd column and its composition turns up to be 48.66 mol% Toluene and 51.34 % o-Xylene. Toluene is the Light key and we will get most of it from top whereas o-Xylene is Heavy key and we will get it from bottom. Here, the temperature of feed is same as the bottom product temperature of column 1 (assuming no temperature drop in transportation) which is 124.3 ºC. The top and bottom temperatures are 115.15 ºC and 141.8 ºC respectively.

The dew point calculations give top temperature as 115.15 ºC and the bubble point calculations give the bottom temperature as 141.8 ºC[19].

Table 4: Energy Calculation summary for Column 2 in conventional sequence columns

For Column 2	
Top Temp.	115.15 ºC
Heat Duty of Condensation	426.1 kW

Feed Temperature	124.3 ºC
Heat in Feed ($F*q*H_F$)	12.745 kW
Bottom Temp.	141.8 ºC
Heat in Residue	12 kW
Heat Duty of Reboiler 2 (5% loss)	446.63 kW

Heat available with the feed is 12.745 kW, heat duty calculations give; heat of condensation in column 2 as 426.1 kW, heat in residue as 12kW and heat load on reboiler with assuming 5% energy losses as 446.63kW.Now, looking over the two columns as one system, the total reboiler duty is 903.11kW and total condenser load is 839.3 kW.

The mass flow rate of the cooling water required is 144.55m^3/h, considering 2% loss during operation the amount of makeup water required 2.89m^3/h. In India, the cost of cooling water is 20₹/m^3. Therefore, cost of makeup water is 57.82₹/h.

Total quantity of steam required is 1350.5kg/h and the rate at which steam is available is 1₹/kg (if not generated in company's own thermal power plant which will be otherwise even lesser), this incurs steam cost for the system as 1350.5₹/h. The total cost of operation sums up to be 1409₹/h. It does not incorporate fixed cost, cost of pumping, instrumentation, and other auxiliaries.

Table 5: Energy and Cost Calculation summary in conventional sequence columns

Overall Calculation	
Total Reboiler Duty	903.11 kW
Mass flow rate of cooling water required	144.55 m^3/h
Loss Considered	2%
Cost of cooling water	20₹/m^3
Cost of makeup water	57.82 ₹/h
Total quantity of steam required	1350.5 kg/h
Rate of steam	1₹/kg
Cost of steam	1350.5 ₹/h
Cost of operation	**1409 ₹/h**

2. **Conventional Dividing Wall Column:** In dividing wall column we have 1 column, 1 condenser and 1 reboiler, which automatically reduce fixed costs by upto 30% [6].Here the feed mixture remains the same and the desired product purities are also kept same. Next, we have three exit streams from the same column shell, each with one component in much higher concentration then the other.

   From the top we will get Benzene 95 mol% and remaining toluene and the top temperature is 82.5 ºC. We have chosen the reference temperature as 80.15 ºC, which is the boiling point of Benzene. Therefore, heat in distillate is 2360.74kJ/h.
   Keeping cooling water as the cooling medium and consistent product purity, the condenser duty is 392.7kW.

   The feed temperature is 100 ºC, with equi-molal mixture of Benzene-Toluene-o-Xylene. The heat with feed is 11.93kW.

From the intermediate part of the shell we get side stream product which is mainly toluene, leaving the column at 107.65 ºC. The heat in side stream product is 10.48kW.

The stripping section of the column is rich with o-Xylene. The bottom temperature is 141.8 ºC. Heat in Residue is 28.22kW.

The reboiler load with 5% losses incorporated is almost 442kW. Cost of steam employed is 742.6₹/hr and cost of makeup cooling water is 27₹/hr. Thus, total cost of operation is 770₹/hr (without cost of pumping, instrumentation, and other auxiliaries).

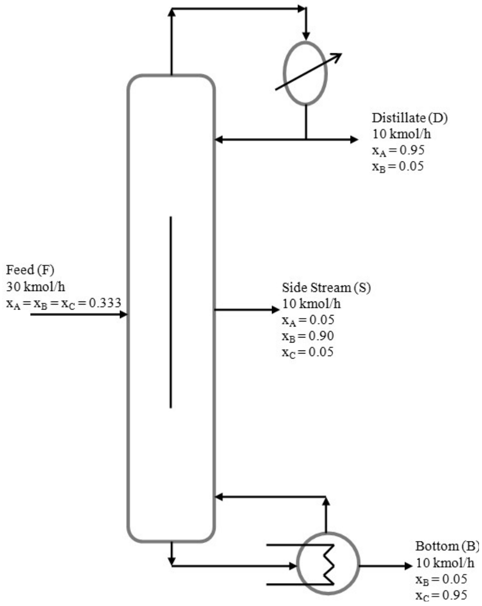

Figure 6: DWC without additional Reboiler/Condenser

Table 6: Energy and Cost Calculations Summary for DWC with MSCM Design Methodology

DWC with MSCM	
Top Temp.	82.5 ºC
Heat Duty of Condensation	392.7 kW
Reference Temp.	353.3 K
Heat in Distillate	2360.74 kJ/h
Feed Temperature	100 ºC
Heat in Feed ($F*q*H_F$)	11.93 kW
Side Product Temp.	107.65 ºC
Heat in Side Stream Product	10.48 kW
Bottom Temp.	141.8 ºC
Heat in Residue	28.22 kW
Heat Duty of Reboiler (5% loss)	441.13 kW
Cost of Steam	742.6 ₹/hr
Cost of Cooling Water	27 ₹/hr
Cost of Operation	**770 ₹/hr**

3. **Suggested Model for DWC:** Here, as mentioned before everything else will remain same, except the problem of inconsistent side stream product and its solution of adding a reboiler, to get the required purity of component B, which is toluene in our case.

Here, the top temperature is 82.5 ºC; the feed temperature is 100 ºC; the side product outlet temperature from column shell is 108.5 ºC; the side product temperature from the system after reboiler is 109.25 ºC and the bottom temperature is 141.8 ºC.

Heat duty of condensation was calculated as 392.7 kW. Taking reference temperature as 353.3 K, we get heat in distillate as 2360.74 kJ/h, heat in feed as 11.93 kW, heat in side product as 9.3 kW, heat in recycle stream as 0.52 kW and heat in bottom product as 28.22 kW. The side stream reboiler load is 7.13 kW and the heat duty of main reboiler is 433 kW (with 5% losses).

Cost of steam employed in operation is 760.67₹/hr. Cost of the cooling water makeup is 27.05₹/hr. Total Cost of operation is 788₹/hr.

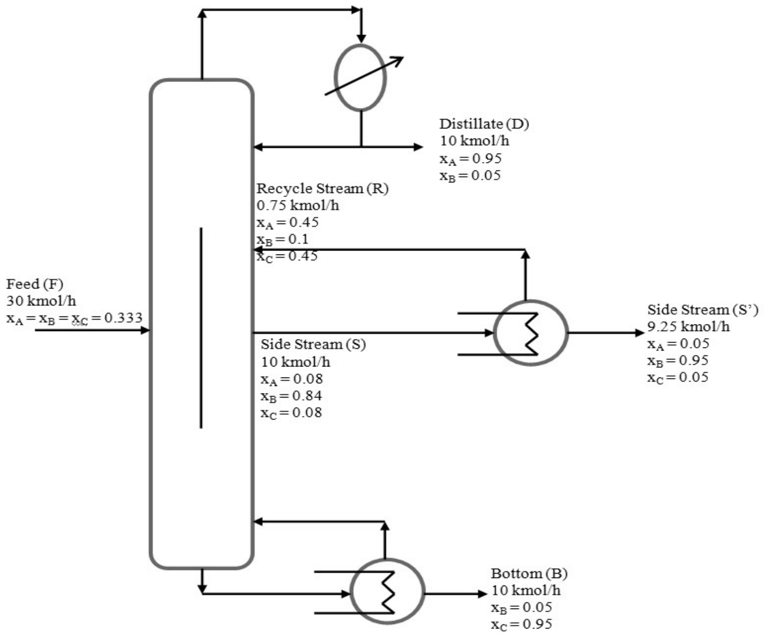

Figure 7: DWC with an additional Reboiler

Table 7: Energy and Cost Calculations Summary for DWC with MSCM Design Methodology with additional reboiler for side stream purity

Suggested Model	
Top Temp.	82.5 ºC
Heat Duty of Condensation	392.7 kW
Reference Temp.	353.3 K
Heat in Distillate	2360.74 kJ/h
Feed Temperature	100 ºC
Heat in Feed ($F*q*H_F$)	11.93 kW

Side Product Temp. (S)	108.5 ºC
Heat in Side Stream Product	9.81 kW
Side Product Temp. (S')	109.25 ºC
Heat in Side Stream Product	9.3 kW
Recycle Stream (Rs)	100.15 ºC
Heat in Recycle Stream	0.52 kW
Heat Duty for Reboiler in side stream	7.13 kW
Bottom Temp.	141.8 ºC
Heat in Residue	28.22 kW
Heat Duty of Reboiler 2 (5% loss)	433 kW
Cost of Steam	760.67 ₹/hr
Cost of Cooling Water	27 .05₹/hr
Cost of Operation	**788 ₹/hr**

VIII. DISCUSSION

The study shows that the dividing wall column inherently requires lesser capital cost compared to sequence of columns for same number of components and degree of separation. Dividing Wall Columns require single shell with not more than three heat exchangers for obtaining exact composition of three component mixtures. Here, as mentioned a suggested column is presented which is to eliminate the real time problem of inconsistent side stream which is generally a case.

In the previous section we have made the relevant heat balances and operating costs. One can see that the condenser and reboiler duties turn up to be less than 50% in either case, which subsequently saved energy by 51.16% for MSCM and 52.05% for more suggested model. Consequently, the utility requirements have also reduced to halves of the conventional multi-column methods.

Moreover, the total cost of operation and thus the percentage savings where computed to be approximately 45.35% of Direct Sequence Column for DWC by MSCM and 44.07% of the former for suggested model consisting of an extra reboiler.

Table 8: Summary Showing Comparison Between Heat Duties For Different Type Of Column Arrangements

Parameter	Direct Sequence Conventional Column	Dividing Wall Column (Designed by MSCM)	Dividing Wall Column (Suggested Model)
Number of Columns	2	1	1
Number of Condenser	2	1	1
Number of Reboiler	2	1	2
Net Condenser Duty (kW)	839.2	392.7	392.7
Net Reboiler Duty (kW)	903.11	441.02	433
Energy Saving	Ref	51.16%	52.05%

Steam Required (kg/h)	1350.5	742.58	760.67
Cooling Water Required (Make up) (m^3/h)	2.891	1.3528	1.3528
Cost of Operation (₹/hr)	1409	770	788
Percentage Saving (Operation)	Ref	45.35%	44.07% (2.34%higher than DWC MSCM)

IX. CONCLUSION

The paper presented here is for developing a modified design for dividing wall column, which was named as Modified Sotudeh and Murlikrishna Combined Method. The method was then turned into a program module, the test results of which were compared with original methods, proving it to be accurate enough for preliminary design of dividing wall column. Also, to overcome a real time issue of inconsistent side product in dividing wall column a separate suggestion of introducing a reboiler/condenser in the side stream is made. The energy calculations performed showed that the dividing wall column saved almost 50% energy then the conventional sequential method which is around 45% of cost saving on operations.

1. Abbreviation

F = Feed Flow Rate in mol/h or kmol/h
FCC = Feed Condition and Composition
DWC = Divided Wall Distillation Column
MSCM = Murlikrishna and Sotudeh Combined Model
D = Distillate Flow Rate in mol/h or kmol/h
L = Liquid Flow Rate in enriching section of the column in mol/h or kmol/h
Ḻ= Liquid Flow Rate in stripping section of the column in mol/h or kmol/h
L_r = Liquid recycle stage
N = Number of trays
N_m = Minimum number of trays
N_r = Number of trays in rectifying/enriching section
N_s = Number of trays in stripping section
q = Feed Quality ($0<q<1$)
R = Actual Reflux Ratio
R_m = Minimum Reflux Ratio
r = Internal Reflux Ratio
$r_{i,B}$ = Fractional Recovery of component ‘i’ in the bottom section of column
$r_{i,T}$ = Fractional Recovery of component ‘i’ in the top section of column
r_m = Minimum internal reflux ratio
S = Side Stream Flow Rate in mol/h or kmol/h
V = Vapour Flow Rate in enriching section of the column in mol/h or kmol/h
$\tilde{V}$ = Vapour Flow Rate in stripping section of the column in mol/h or kmol/h
V_r = Vapour recycle stage
W = Residue Flow Rate in mol/h or kmol/h
x = mole fraction of component in liquid phase
y = mole fraction of component in vapour phase

z = mole fraction of component in feed

2. Greek Symbols

α = Relative Volatilities of component with respect to Light Key Component
β = Split between the Light Key Component and Heavy Key Component.
θ = Roots of the Underwood's Equation

3. Subscripts

i = refers to component specified {A,B,C}
A,B,C = components, with A being most volatile and C least volatile
1,2,3 = Various sections of the column
f = molar flow rate of component in feed in mol/h or kmol/h
min = minimum
p = preferred
r = rectifying/enriching section
s = stripping section

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