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RESEARCH ARTICLE

DESIGN OF DISTILLATION COLUMN FOR HANDLING HIGH DENSITY FERMENTED WASH IN BIOREFINARIES

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ABSTRACT

Design of distillation column is a crucial task and becomes even more difficult when deals with high density foaming liquids like fermented wash. Fermented wash is a high density liquid (alcohol-water mixture) produced as a product of fermentation of molasses by yeast *Saccharomyces cerevisiae*. Almost 99 % of biorefinaries employ distillation for recovery and concentration of ethanol from fermented wash. Since distillation is the highly energy intensive operation, it consumes almost 60 % of the total energy consumption of any distillery. Therefore optimization of distillation, to reduce the energy consumption is necessary. In view of this, the major areas where there is a possibility of energy optimization are identified. Wash handling column is one of such highly energy intensive area. Also there are operational difficulties like foaming and chocking of the trays due to higher density of fermented wash. The paper in details covers the modeling and development of excel program for design of distillation column. The papers also explain the newly designed parameters for design of distillation column to make it compatible for operating in multi-pressure distillation.

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INTRODUCTION

Humphrey and Keller (1997) reported that distillation is a most widely used separation technique in chemical and allied process industries, and approximately account for 90–95% of all the separations. Design of distillation process for any distillery is a critical task. The optimization efforts like heat integration make it even more critical. Design of distillation column includes consideration of different parameters as shown in Table 1. Also the various problems occurring during the operation of column like entrainment, flooding, foaming and weeping needs to be taken care. These problems arise due to adverse vapour flow conditions. Fluctuation in steam flowrate causes adverse effects on the column performance. Sudden reduction in steam flowrate causes reduction in the amount of heat input to the column. This reduced energy input causes less vapour generation resulting in inadequate supply of vapours in a column than that required for normal operation i.e. required to maintain vapour-liquid equilibrium in the column. In such consequences, liquid on the tray dumps down on its immediate lower tray and this phenomenon continues till all the liquids on the trays get collected at the bottom of the column and is known as weeping. On contrary, sudden rise in steam flowrate causes increase in amount of heat input to the column. This increased energy input causes more vapour generation resulting in supply of surplus vapours in a column than that required for normal operation i.e. required to maintain vapour-liquid equilibrium in the column. In such consequences, liquid on the tray get carried with high velocity vapours resulting in inadequate liquid hold-up on tray which ultimately leads to poor vapour liquid contact. This phenomenon is known as entrainment. No doubt, this phenomenon reduces the efficiency of trays; but sometimes it could be detrimental when low volatile material is carried to its immediate higher plate holding a liquid of higher volatility and contaminate high purity distillate. Excessive entrainment can lead to flooding.

Excess vapour flow is responsible for flooding in the column. In this phenomenon high pressure from excessive vapour backs up the liquid in the downcomer, causing rise in liquid holdup on the tray above. Depending on the degree of flooding, the maximum capacity of the column may be severely reduced. Flooding is detected by sharp increases in column differential pressure and significant decrease in separation efficiency. According to Kister (1992), flooding occurs due to one of the

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following reasons: spray entrainment flooding; froth entrainment flooding; malfunctioning of down-comer and defects in large diameter columns (Ujile and Iminabo, 2014). Flooding capacity can be well determined by Kister and Haas method and Fair's correlation method proposed by Perry (2008). These methods are utilized to evaluate and compare flooding capacity for distillation column. Unlike flooding, foaming refers to the expansion of liquid due to passage of vapour or gas. Although it provides high interfacial liquid-vapour contact, excessive foaming often leads to liquid buildup on trays. It means though the circumstances in which these malfunctions occur are different; the effect of these malfunctions is same. Sometimes foaming is so severe that foam mixes with liquid on the tray above. Foaming primarily depends on physical properties of liquid mixtures; however it is quite possible that tray designs and operating condition may leads to it. Irrespective of its causes, effects are always unfavorable resulting in a reduction in separation efficiency of the column. Of these problems, foaming in column is a most severe and occurs primarily due to physical properties of the liquid mixtures like density and also on tray designs. In this paper, it is therefore decided to design the column with due consideration of its properties like density.

Design of Distillation Column

In multi-pressure distillation section of any distillery, various columns perform different functions. The functioning of different columns is as mentioned below.

Analyser Column - To Strip off alcohol from fermented wash
Degassifying Column - To remove non-condensables from fermented wash
Pre-Rectifier Column - It is principally used for removal of low boiling impurities from top and high boiling impurities in the form of fusel oils from side streams
Extractive Distillation Column - It is principally used to remove impurities based on principle of hydro extraction. Dilution water to column is feed in such a way that it selects the higher alcohol and other impurities to move upward and extract ethanol down
Rectifier Column - It is principally used for removal of low boiling impurities from top and high boiling impurities in the form of fusel oils from side streams. It operates the way in which Pre-Rectifier operates.
Recovery Column - This column removes heavy impurities in the form of fusel oil and concentrates them in the form of fusel oil that are coming in the form of rectifier column
Simmering Column - Simmering column is principally used for removal of methanol and diacetyl from Extra Neutral Alcohol (ENA)

Of these seven columns, first two columns namely Analyzer and Degassifying operates on high density fermented wash and therefore needs to be designed by considering different foaming velocities, tray spacings and foaming system factors. After considering the functioning of these columns and prevailing operating conditions, design of columns is completed. The parameters for design of distillation section are as in table 1. In normal course, when column is subjected for less dense liquids; percentage flooding considered during design of column is 70 %. However, when column is subjected for high density liquids like fermented wash, percentage flooding considered during design of column is 35 %.

Table 1. Process parameters for design of distillation column

S. No.	Process Parameter	Notation	Unit
1	Vapor Load	V	Kg/hr
2	Liquid Load	L	Kg/hr
3	Temperature @ Top of Column	T_1	^{0}C
4	Pressure @ Top of Column	P_1	bar(a)
5	Concentration @ Top of Column	C_0	% V/V
6	Concentration @ Top of Column	C_1	%W/W
7	Concentration @ Top of Column	C_2	% mole/mole
8	Density of Ethanol @ T_1	ρ_1	Kg/m^3
9	Density of Water	ρ_2	Kg/m^3
10	Design Margin	D_M	%
11	Design Vapor Load	D_{VL}	Kg/hr
12	Design Liquid Load	D_{LL}	kg/hr
13	Average Molecular Weight of Vapor	M_W	Kg/Kmol
14	Vapor Density @ Top of Column	ρ_V	Kg/m^3
15	Vapor Load	V_1	m^3/hr
16	Liquid Density	ρ_L	Kg/m^3
17	Liquid Vapor Flow Parameter	f_{1V}	
18	Tray Spacing		mm
19	Vapor Flow Parameter	C_{SB}	
20	% Flooding in the Column	$F_{\%}$	%
21	Foaming System Factor		
22	Flooding Velocity	U_f	m/s
23	Final Flooding Velocity	U_{ff}	m/s
24	Down Comer Area	A_d	%
25	Column Diameter	D	mm

Design Basis for Distillation Section

Different parameters that need to be considered during design are mentioned in Table 2. These parameters are very important from design point of view.

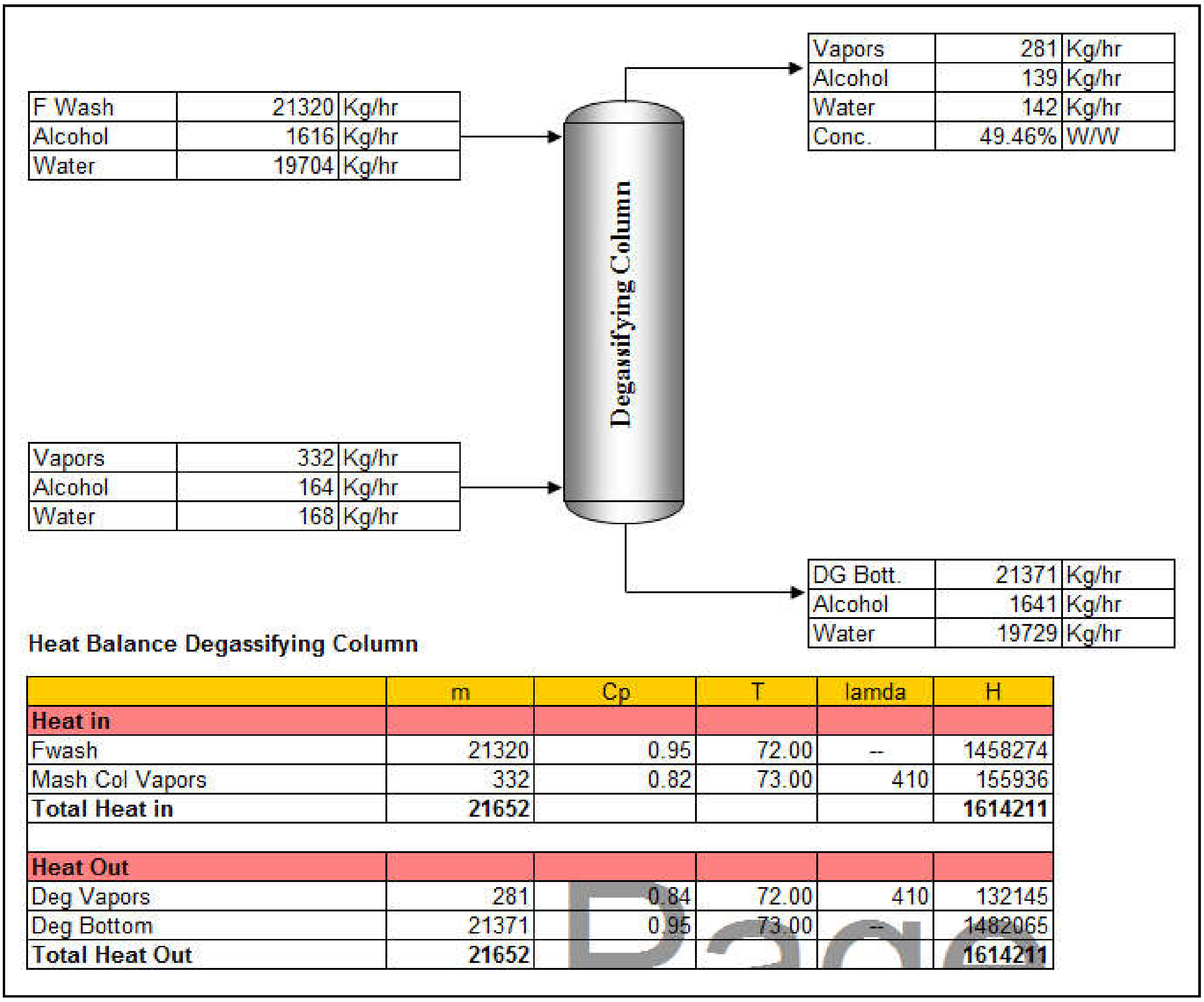
Table 2. Basis for design of distillation section in developed configuration

S.No.	Parameters	Values	Units
1	Plant Capacity - Total	50.0	KLPD
2	TA Cut	6.5%	
3	Plant Capacity - ENA	46.75	KLPD
4	TA cut Produced	3.250	KLPD
5	100% Alcohol Produced	48.0	KLPD
6	Fermentation Efficiency	90.00	%
7	Distillation Efficiency	98.50	%
8	Fermented Wash Alcohol Concentration	10.0%	v/v
9	Design Margin	0	%
10	ENA	96%	v/v
11	Total Spirit	96%	v/v
12	DG Load (% of Analyser Vapours)	10%	w/w
13	Specific Gravity of Alcohol	0.796	
14	Specific Gravity of Fermented Mash	1.05	
15	Cooling Water Supply Temperature	32.0	Deg C
16	Cooling Water Return Temperature	42.0	Deg C
17	Total Solid Content in Molasses	80%	w/w
18	Total Dissolved Solids in F.W.	97%	w/w

In reference to the parameters mentioned above the design of the column was carried out. Though design of column follows same design procedure; the involved parameters changes from column to column as mentioned in Table 3. Procedure for design of distillation column is adopted from Patil et al. (2016). Following parameters needs to be input to ChemCAD (ChemCAD) simulation software for simulation of individual distillation columns and whole configuration. All the heat and mass balance charts shown below are prepared from simulation results of distillation columns. Different parameters considered during design of individual equipments are as shown in Table 1.

Table 3. Designed parameters for different columns based on the properties of liquid they are handling

S. No.	Process Parameter	Notation	Designed Values for Analyser Column	Degassifying Column	Pre-Rectifier Column	Extractive Distillation Column	Rectifier Column	Recovery Column	Simmering Column	Unit
1	Average Mol. Weight of Vapor	M_W	23.40	23.40	41.60	18.90	42.40	41.90	42.70	Kg/Kmol
2	Vapor Density @ Top of Column	ρ_V	0.3413	0.3279	2.97	0.32	3.02	1.45	1.51	Kg/m^3
3	Vapor Load	V_1	11881.00	1237.00	2147.00	3450.00	3009.00	606.00	1747.00	m^3/hr
4	Liquid Density	ρ_L	1020.00	1020.00	739.00	983.36	735.32	807.73	805.21	Kg/m^3
5	Liquid Vapor Flow Parameter	f_{1V}	0.0815664	0.7994807	0.06336	0.2717	0.0641	0.0424	0.0433	
6	Tray Spacing		750.00	750.00	250.00	300.00	250.00	250.00	250.00	mm
	Tray Type		RH Grid	RH Grid	Bubble-cap	Bubble-cap	Bubble-cap	Sieve	Sieve	
7	Vapor Flow Parameter	C_{SB}	0.1113314	0.0463385	0.0560	0.0474883	0.0559452	0.0579229	0.0578340	
8	% Flooding in the Column	$F_{\%}$	35.00	35.00	70.00	50.00	70.00	70.00	70.00	%
9	Foaming System Factor		1.00	1.00						
10	Flooding Velocity	U_f	6.10	2.60	0.90	2.60	0.90	1.40	1.30	m/s
11	Final Flooding Velocity	U_{ff}	2.13	0.90	0.60	1.30	0.61	0.95	0.90	m/s
12	Down Comer Area	A_d	12.00	12.00	9.00	12.00	12.00	9.00	9.00	%
13	Column Diameter	D	1500.00	750.00	1165.00	1050.00	1425.00	500.00	850.00	mm



F Wash	21320	Kg/hr
Alcohol	1616	Kg/hr
Water	19704	Kg/hr

Vapors	332	Kg/hr
Alcohol	164	Kg/hr
Water	168	Kg/hr

Vapors	281	Kg/hr
Alcohol	139	Kg/hr
Water	142	Kg/hr
Conc.	49.46%	W/W

DG Bott.	21371	Kg/hr
Alcohol	1641	Kg/hr
Water	19729	Kg/hr

Heat Balance Degassifying Column

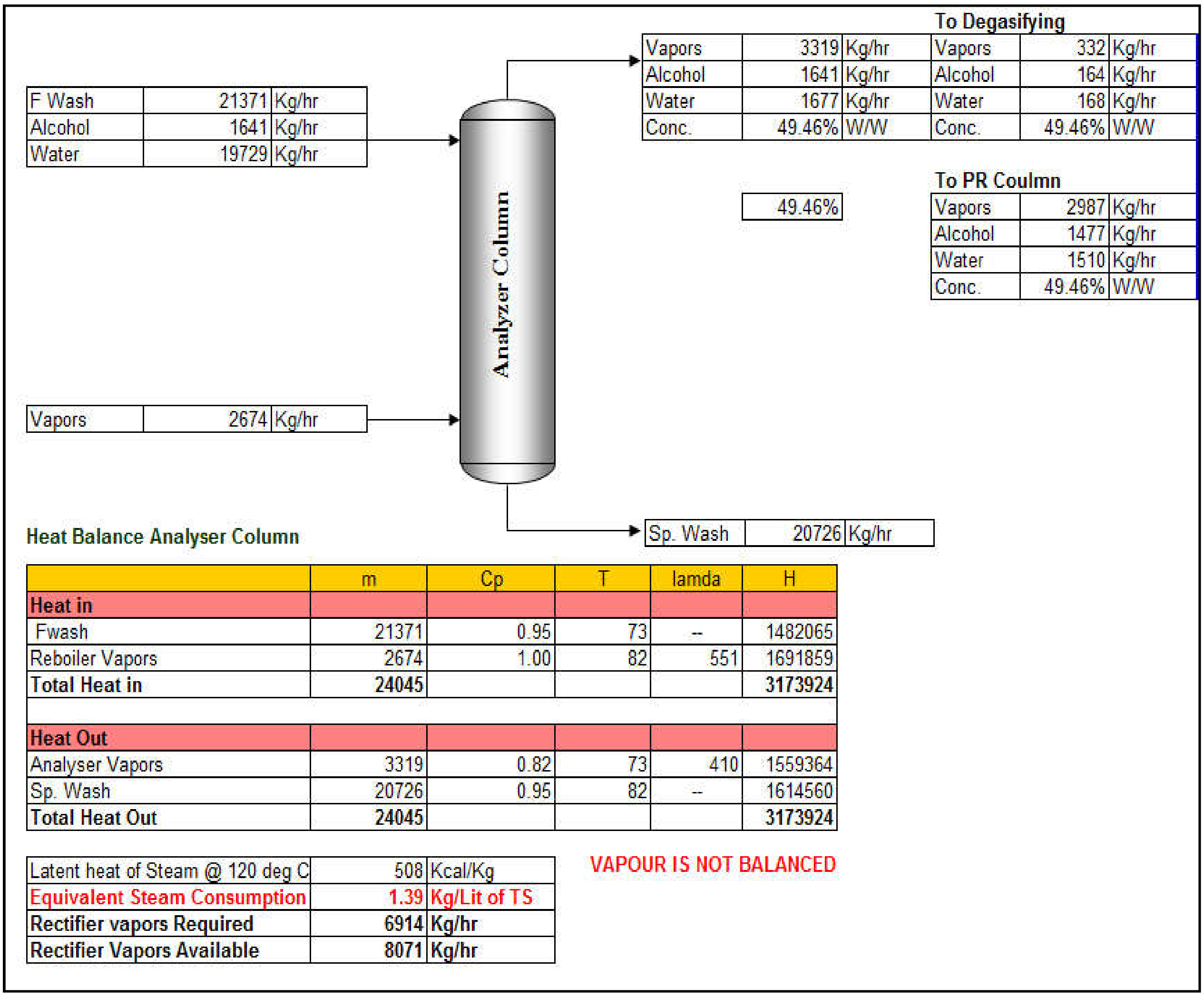
	m	Cp	T	lamda	H
Heat in					
Fwash	21320	0.95	72.00	--	1458274
Mash Col Vapors	332	0.82	73.00	410	155936
Total Heat in	**21652**				**1614211**
Heat Out					
Deg Vapors	281	0.84	72.00	410	132145
Deg Bottom	21371	0.95	73.00	--	1482065
Total Heat Out	**21652**				**1614211**

Figure 1. Heat and mass balance across degassifying column

Table 4. Sizing of degassifying column

S. No.	Process Parameter	Notation	Values	Unit
1	Vapor Load	V	455.36	Kg/hr
2	Liquid Load	L	20304.57	Kg/hr
3	Temperature @ Top of Column	T_1	70.00	^{0}C
4	Pressure @ Top of Column	P_1	0.4	bar(a)
5	Concentration @ Top of Column	C_0	45	% V/V
6	Concentration @ Top of Column	C_1	37.78	% W/W
7	Concentration @ Top of Column	C_2	19.20	% mole/mole
8	Density of Ethanol @ T_1	ρ_1	742.00	Kg/m^3
9	Density of Water	ρ_2	1000	Kg/m^3
10	Design Margin	D_M	0	%
11	Design Vapor Load	D_{VL}	455.36	Kg/hr
12	Design Liquid Load	D_{LL}	20305	kg/hr
13	Average Molecular Weight of Vapor	M_W	23.4	Kg/Kmol
14	Vapor Density @ Top of Column	ρ_V	0.3279	Kg/m^3
15	Vapor Load	V_1	1389	m^3/hr
16	Liquid Density	ρ_L	1020.00	Kg/m^3
17	Liquid Vapor Flow Parameter	f_{1V}	0.7994807	
18	Tray Spacing		750	mm
19	Vapor Flow Parameter	C_{SB}	0.0463385	
20	% Flooding in the Column	$F_{\%}$	35	%
21	Foaming System Factor		1	
22	Flooding Velocity	U_f	2.6	m/s
23	Final Flooding Velocity	U_{ff}	0.904	m/s
24	Down Comer Area	A_d	12	%
25	Column Diameter	D	800	mm

The material and energy balance across simulated analyzer column is as shown in Figure 2 whereas sizing of analyzer column is as shown in Table 5.



F Wash	21371	Kg/hr
Alcohol	1641	Kg/hr
Water	19729	Kg/hr

Vapors	2674	Kg/hr

Vapors	3319	Kg/hr
Alcohol	1641	Kg/hr
Water	1677	Kg/hr
Conc.	49.46%	W/W

To Degasifying

Vapors	332	Kg/hr
Alcohol	164	Kg/hr
Water	168	Kg/hr
Conc.	49.46%	W/W

To PR Coulmn

Vapors	2987	Kg/hr
Alcohol	1477	Kg/hr
Water	1510	Kg/hr
Conc.	49.46%	W/W

Sp. Wash	20726	Kg/hr

Heat Balance Analyser Column

	m	Cp	T	lamda	H
Heat in					
Fwash	21371	0.95	73	--	1482065
Reboiler Vapors	2674	1.00	82	551	1691859
Total Heat in	**24045**				**3173924**
Heat Out					
Analyser Vapors	3319	0.82	73	410	1559364
Sp. Wash	20726	0.95	82	--	1614560
Total Heat Out	**24045**				**3173924**

Latent heat of Steam @ 120 deg C	508	Kcal/Kg
Equivalent Steam Consumption	1.39	Kg/Lit of TS
Rectifier vapors Required	**6914**	**Kg/hr**
Rectifier Vapors Available	**8071**	**Kg/hr**

Figure 2. Heat and mass balance across analyzer column

Table 5. Sizing of analyzer column

S. No.	Process Parameter	Notation	Values	Unit
1	Vapor Load	V	4553.57	Kg/hr
2	Liquid Load	L	20304.57	Kg/hr
3	Temperature @ Top of Column	T_1	73.00	^{0}C
4	Pressure @ Top of Column	P_1	0.42	bar(a)
5	Concentration @ Top of Column	C_0	45	% V/V
6	Concentration @ Top of Column	C_1	37.78	% W/W
7	Concentration @ Top of Column	C_2	19.20	% mole/mole
8	Density of Ethanol @ T_1	ρ_1	742.00	Kg/m^3
9	Density of Water	ρ_2	1000	Kg/m^3
10	Design Margin	D_M	0	%
11	Design Vapor Load	D_{VL}	4553.57	Kg/hr
12	Design Liquid Load	D_{LL}	20305	kg/hr
13	Average Molecular Weight of Vapor	M_W	23.4	Kg/Kmol
14	Vapor Density @ Top of Column	ρ_V	0.3413	Kg/m^3
15	Vapor Load	V_1	13342	m^3/hr
16	Liquid Density	ρ_L	1020.00	Kg/m^3
17	Liquid Vapor Flow Parameter	f_{1V}	0.0815664	
18	Tray Spacing		750	mm
19	Vapor Flow Parameter	C_{SB}	0.1113314	
20	% Flooding in the Column	$F_{\%}$	35	%
21	Foaming System Factor		1	
22	Flooding Velocity	U_f	6.1	m/s
23	Final Flooding Velocity	U_{ff}	2.130	m/s
24	Down Comer Area	A_d	12	%
25	Column Diameter	D	1600	mm

Column name – Analyzer
General top pressure – 0.45 kg/cm2
Calculated pressure drop – 40 X 20 = 800/10000 = 0.08 kg/cm2
Number of stages – 20 = 10000 mm of water)
Feed tray – 1
Simulation model – Regular VLE model
Efficiency @ top stage – 0.65
Efficiency @ last stage – 0.65
Condenser mode – No condenser
Reboiler duty – 3173924 kcal/hr

Table 3 clears that foaming system factor needs to be considered only in case of high density liquids. It is not applicable for column handling alcohol-water mixture. Also the flooding velocity used in designing columns for high density liquids is much higher than that required for columns handling lower density liquids. Also the columns handling high density fermented wash needs almost triple tray spacing as compared to that of regular columns handling alcohol-water mixture of lower density. It is assumed that vapours leaving each tray are in equilibrium with liquid leaving same tray. This analysis assumes that each tray is operating at 100% efficiency. However due to insufficient contact time and degree of mixing, in actual practice trays are not perform at 100% efficiency. It means, in actual operation, vapours and liquid leaving the same tray are not in equilibrium. Therefore in order to achieve desired separation, additional trays need to be incorporated in a distillation column. The actual number of trays needs to be added is calculated by using trays efficiency. As far as tray efficiencies are concerned, two efficiencies namely overall efficiency and Murphree efficiency are considered. Overall tray efficiency is defined as the ratio of number of theoretical trays to number of actual trays (Cardona and Sanchez, 2007). Also the trays needed to handle the fermented wash are specially designed RH Grid trays that have enough strength to bear the weight of heavy fermented wash. Use of these trays solves the problem of weeping and chocking arising in sieve trays and bubble-cap trays respectively. In case of bubble-cap trays there is a possibility of frequent chocking due to presence of high amount of suspended solids and mud in fermented wash. Chocking of caps on trays leads to different severe consequences like uncontrolled pressure build-up and flooding in column. The newly designed geometry of tray directs the vapour flow through the pool of liquid on a tray horizontally enhancing the performance of tray thereby making more vapour liquid contact. Also these trays provide enough vapour disengagement space. Bhole et al. (2016) also developed a new single stage distillation technique with artificial irrigation by external re-circulation pump. After successful testing of technique for methanol-water system, he concluded that irrigation in stage by external re-circulation pump offers significant enhancement in rectification and is clearly observed in terms of increased MVC (Methanol) concentration in distillate.

Material and Energy Balance

The material and energy balance across simulated degassifying column is as shown in Figure 1 whereas sizing of degassifying column is as shown in Table 4.

Conclusion

Flooding in distillation column is a collective effect of change in flow regime of vapour and liquids flowrates in a column and cause loss of separation thereby substantially reducing the energy efficiency of process. Design and subsequent simulation runs of distillation column reveals that flooding velocity is an important parameter to be considered during design of column. It is observed that design of distillation column for high density fermented wash consider almost triple flooding velocity as compared to that considered for alcohol-water mixture. The foaming nature of fermented wash also tends to consider for high trays spacings to compensate for enough vapour-liquid disengagement space.

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