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Multicomponent rectification: Representation of number of stages as function of reflux ratio

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Abstract

The goal of this contribution is to provide some general guidelines for the distillation column design despite of particular deviations and tencendes. It is not an accurate and universal correlation of the number of stages and reflux, just the verification of some usually used heuristics and a global vision of multiple situations. It is demonstrated that the heuristics that fixes the optimal reflux as 1.2 to 1.5 times the minimal reflux is valid independently of the energy and steel cost variations. Obviously, when the energy becomes more expensive is preferable to work near the 1.2 factor. The Gilliland correlation is reconsidered under the light of the new computational power and available simulation software.

Keywords: Optimal reflux, Gilliland, simulation, reactive distillation

1. Introduction

Gilliland (1940) found a way to represent graphically the number of stages versus the reflux where several systems followed the same curve with small deviations. Some systems as the ethanol-water do not follow this general tendency; it was pointed out but not studied. The rule of thumb that the optimal reflux is around 1.2 to 1.5 times the minimal reflux corresponds usually at his coordinate axe from 0.1 to 0.33. Until then, usually, the number of plates (N) was represented directly as function of reflux ratio (r) (figure 1). Then the minimal reflux ratio (r_{min}) and the minimal number of stages (N_{min}) are the horizontal and vertical asymptotes of a curve. It has been demonstrated that the elbow of this curve corresponds to a flat minimal cost where the optimal operation zone is (Bonet et al, 2005). It is quite intuitive to imagine that, the investment costs are too high at the left side of the elbow and the operating costs are too high at the right side.

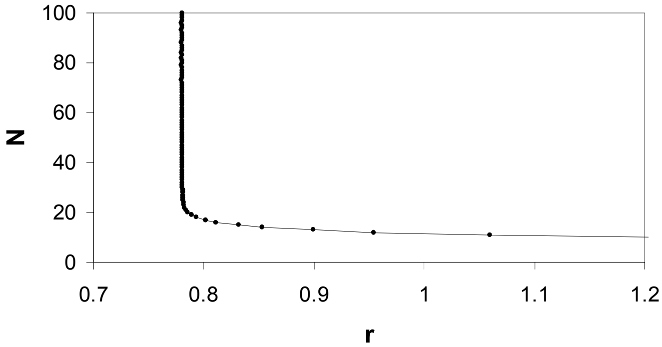

Figure 1 – Reflux and number of stages for a methanol (0.1) – acetone (0.1) – water (0.8) feed mixture, feed at boiling point, P = 101325 Pa, D/F = 0.2063 and x_B (acetone) = 0.995.

The idea of Gilliland was to transform the individual asymptotic limiting conditions of r_{min} and N_{min} to common definite points for any system. When the limiting conditions are the same, then all the curves become quite coincident. All the feasible range of pair of values r and N can be plotted into 0 to 1 axis using the Gilliland graphic. To check this, Gilliland take some data from the literature. The deviations from the general tendency were attributed to aspects such as the existence of various feasible correlations, the feed was not introduced at the optimum location, or N_{min} or r_{min} were not enough accurately calculated. However, these deviations of the general tendecy were not further considered by Gilliland because it was well within the accuracy known for stage efficiencies.

There are a great number of papers trying to linearize or fit the graphical representation of Gilliland to a mathematical function (Molokanov et al, 1971; Al-Ameeri et al, 1985; McCormick, 1988). Some other authors try to improve the exactitude by improving the minimum reflux estimation for multicomponent mixtures (Shoeaei et Tedder, 1987). Gilliland postulated that his correlation has to be used with caution for mixtures of abnormal volatilities such as ethanol and water. Bieker and Erdmann (1990) stated that Gilliland correlation can estimate normal and difficult separations, whereas easy separations with high separation factor are often better than expected from the Gilliland correlation. On the other hand, Barna and Ginn (1985) found that the number of stages at low reflux ratios was higher than was proposed by Gilliland. An interesting property of Gilliland correlation is that it can be applied independently to each column section (Youssef et al, 1989). Gilliland is still used nowadays at the first stages of column design and it is used as a base for new shortcut models (Gadalla et al, 2003).

Nowadays, there are powerful computers and chemical process simulators. At the universities, the students do several simulation practices. This paper presents a high amount of data collected from our courses and our own simulations provided by thousands of column simulations. Before proposing the systems to the students, the infinite/infinite analysis is used to asses the faisability (Güttinger and Morari, 1999; Bonet et al, 2007). The Gilliland graphic is recalculated and evaluated from the point of view of rigorous simulations.

2. Methodology

A single feed column of fixed feed stream has five degrees of freedom according the MESH model. These degrees of freedom can be fixed by five variables such as the number of stages, pressure, an output flow rate (distillate or bottoms), the purity of one of the collected key components and the feed plate position. The output flow rate used to recalculate the Gilliland cases is determined by a mass balance over the column with his distillate and bottom compositions. The reflux ratio is calculated according the desired key component purity as design specification. The feed plate position is a discrete variable and it is determined by a sensitivity analysis while all the other variables are fixed. The optimal feed plate position is which provides a minimal reflux. The optimal feed plate position is very pronounced when the number of stages is near the minimum and it becomes uncertain in a flat minimum reflux at high number of stages, a column near optimal conditions presents a quite rounded minimum (figure 2).

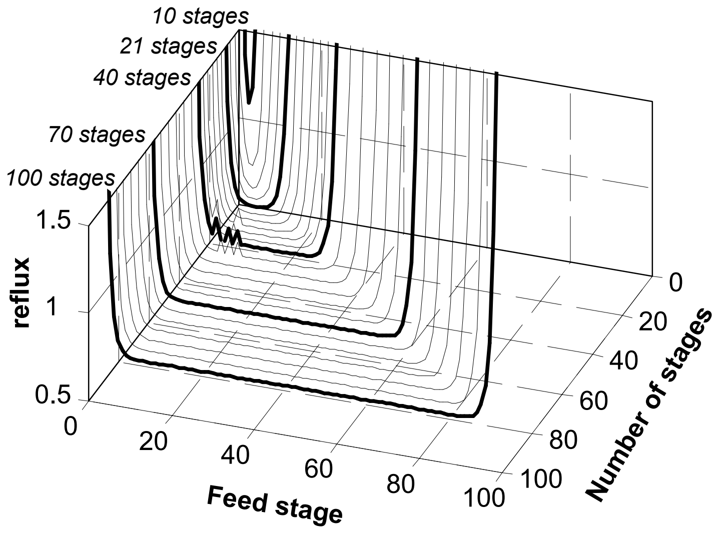

Figure 2– Reflux, number of stages and feed stage for a methanol (0.1) – acetone (0.1) – water (0.8) feed mixture, feed at boiling point, P = 101325 Pa, D/F = 0.2063 and x_B (acetone) = 0.995.

The idea of Gilliland was to use common limits at the graphic using the asymptotic values of minimal number of stages and minimal reflux. The minimal reflux is determined easily with a simulator by using a distillation column with a huge number of stages and feed plate at the middle. It is not applicable to the minimal number of stages as the simulators works only with entire values for the number of stages. The minimal number of stages (N_{min}) is determined by the limiting condition to unity of the graphic of Gilliland or according to the next integral of the x~y vapor liquid equilibrium diagram from the bottoms (x_B) to the distillate (x_D) composition where y is the vapor composition in equilibrium with the liquid composition x:

$$N_{\min} = \int_{x^B}^{x^D} \frac{1}{y-x}\,dx \qquad (1)$$

Gilliland compared his representation with the most common representations until then. In this paper, the Gilliland and N/N$_{\min}$ versus r/r$_{\min}$ representations are considered and compared. Gilliland representation covers all the feasible operation conditions of number of stages and reflux but, from a practical and industrial point of view, the operation conditions are in a limited zone and not to conditions requiring a huge number of stages or reflux. The most common rules of thumb are referred to the ratio of the reflux or number of stages and its corresponding minimal value, so it is interesting to evaluate the shape of this representation. Furthermore, as any mixture on this representation has the same horizontal and vertical asymptotes at unity, a coincidence of courves is expected as in Gilliland's representation. A simple correlation equation for this representation is proposed.

The number of stages is a discrete variable and therefore it is used as input in order to find a reflux that satisfies exactly the product purity required. When the column sections are considered independently, there is not a direct correlation of number of stages and reflux at each section and this produces a stepwise shape on the graphic representation. It is more accentuated at low number of stages. At high number of stages it is difficult to establish the optimal feed plate as has been shown in figure 2. Finally, its capability on correlating a reactive distillation column is also evaluated. It is applied to the first column of a reactive pressure swing distillation presented by Bonet et al. (2005). The calculations are performed by a tray by tray calculation from the feed stage to the distillate and bottoms assuming constant molar overflow on the vapor phase.

All the data are presented at the annex. The feed compositions of the systems taken from Gilliland are in Table 1 and the new ones on Table 2. The corresponding variables used in the simulations are presented in Table 3. The results of the optimized columns are tabulated at the annexes.

3. Results

The rigorous simulation results show that most of the Gilliland's case systems follow the same tendency curve (figure 3) although some simulations could be at different pressure or thermodynamic parameters as this data was not specified by Gilliland. The small deviations observed by Gilliland from the general tendency are also observed in this graphic; therefore the deviations are not due to calculation inaccuracies.

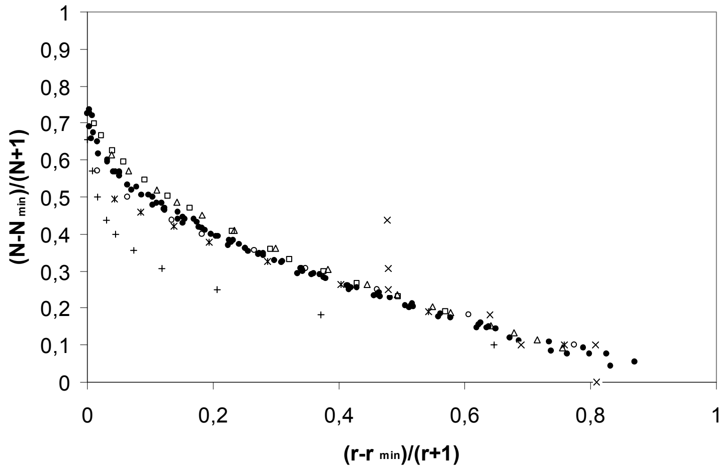

Figure 3- Representation of the Gilliland cases recalculated by rigorous simulation.

It is quite surprising that the number of stages become correlated with the reflux because that could mean some univoque correlation between the N_{min} and r_{min}. Against this, it is well known that N_{min} is constant for a binary distillation with a fixed bottom and distillate compositions whereas the feed composition affects only to r_{min} (figure 4). Changing the feed composition for the case I of Gilliland, a graphic with some non coindicent curves is obtained although most of them follow a similar way (figure 5). Figure 6 shows that N_{min} is between 2 and 10 times r_{min} but this is not enough to justify the coincidences. For a fixed N_{min}, if N is also fixed and r_{min} changes due the feed composition, then that means that r must change accordingly to keep $(r-r_{min})/(r+1)$ almost constant. Figure 7 shows that the constant values are due to a flat maximum. A representation of r/r_{min} also produces a flat zone (figure 8).

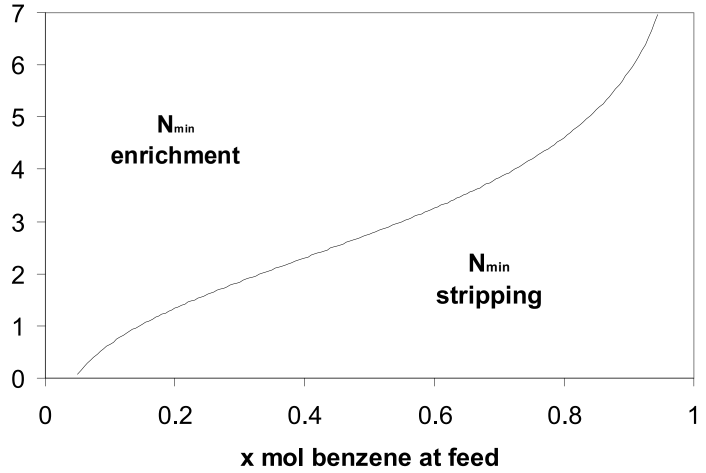

Figure 4- Optimal feed for the Gilliland first case using his representation. (Benzene – toluene; molar fraction of 0.05 benzene at bottom and 0.95 at distillate).

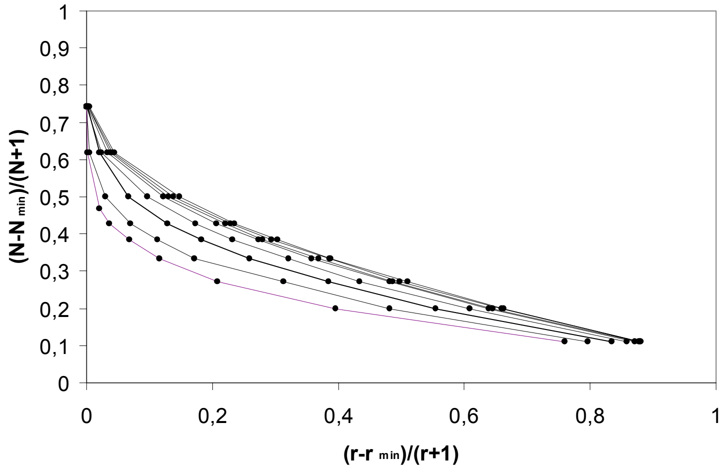

Figure 5- Sensibility analysis of the feed composition for the Gilliland first case using his representation. (Benzene – toluene; molar fraction of 0.05 benzene at bottom and 0.95 at distillate).

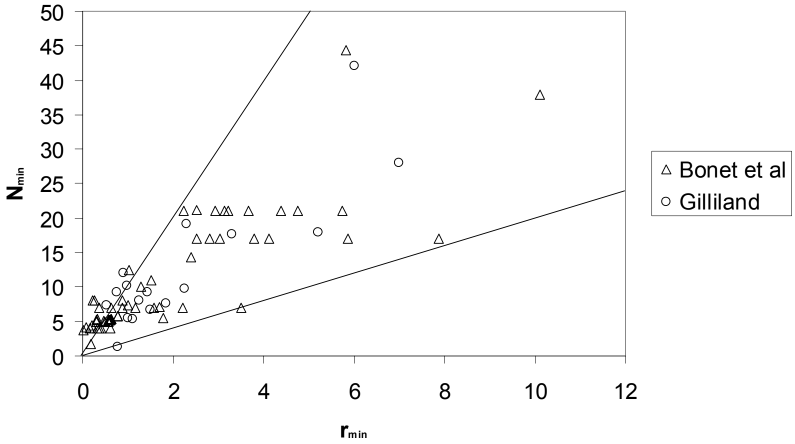

Figure 6- Correlation between the minimal variables of distillation columns.

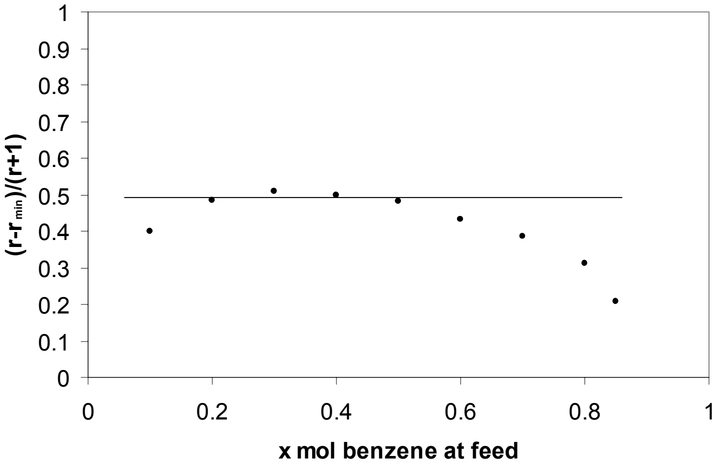

Figure 7- Sensibility analysis of the feed composition on the reflux for the Gilliland first case using his representation. (Benzene – toluene; molar fraction of 0.05 benzene at bottom and 0.95 at distillate).

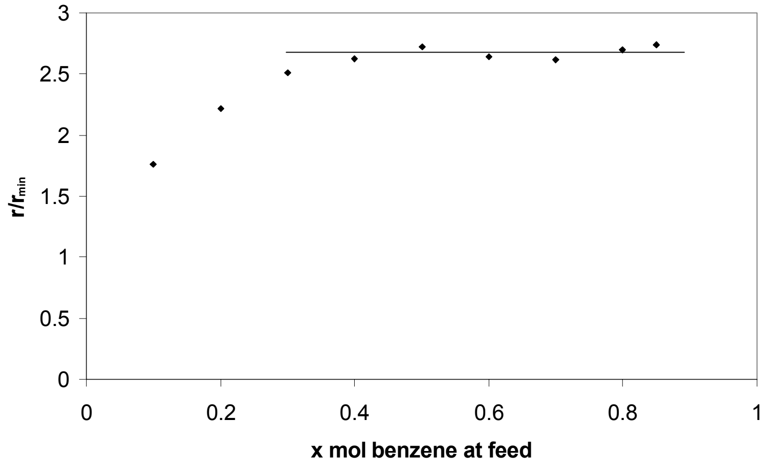

Figure 8- Sensibility analysis of the feed composition on the reflux for the Gilliland first case. (Benzene – toluene; molar fraction of 0.05 benzene at bottom and 0.95 at distillate).

The representation of all the evaluated points including abnormal volatility systems on the Gilliland graphic does not shows a so nice curve as for the Gilliland studied cases (figure 9). However, all the points give us an idea of a general tendency. The first calculated points where the reflux costs are predominant are symbolized by squares and the points where the investment costs are predominant are symbolized by rounds. Accordingly to the graphic an acceptable value for any distillation column could be:

$$\frac{N-N_{\min}}{N+1}=0.45\,;\quad \frac{r-r_{\min}}{r+1}=0.1 \tag{2}$$

Another feasible representation of the data would be the represented on figure 10. Whereas the optimal zone at the Gilliland representation is rather scattered, it is more delimited for this other representation. The next rules of thumb are verified:

$$1.2\le\frac{r}{r_{\min}}\le 1.5\,;\quad 1.5\le\frac{N}{N_{\min}}\le 2.5 \tag{3}$$

It can be stated that the optimal zone is independent of the energy and steel cost fluctuations because the optimal zone is defined by the elbow of the curve as shown in figure 1. Nowadays, the energy consumption must be minimized in order to reduce costs and minimize the pollution on the environment; hence it would be preferable to work at the upper left side of the optimal zone. According to this, an acceptable values as initialization for the design of most of the columns could be:

$$\frac{r}{r_{\min}}=1.2\,;\quad \frac{N}{N_{\min}}=2.1 \tag{4}$$

A simple correlation of this curve could be approximated by the equation 5. Figure 11 shows a zoom of the optimal zone with the proposed points for the initialization of a column design.

$$\frac{N}{N_{\min}} = \left(\frac{0.4}{\frac{r}{r_{\min}} - 0.8} + 1.2 \right) \tag{5}$$

The Gilliland's and the proposed graphical representations of a four component non ideal mixture, with azeotropes which are sensible to pressure, in an entire reactive column with a single feed show also a similar tendency for all the situations (figure 12 and 13). Again, the reason seems to be that the optimal operation conditions are around a flat maximum curve as figure 14 shows for a N/Nmin = 1.84.

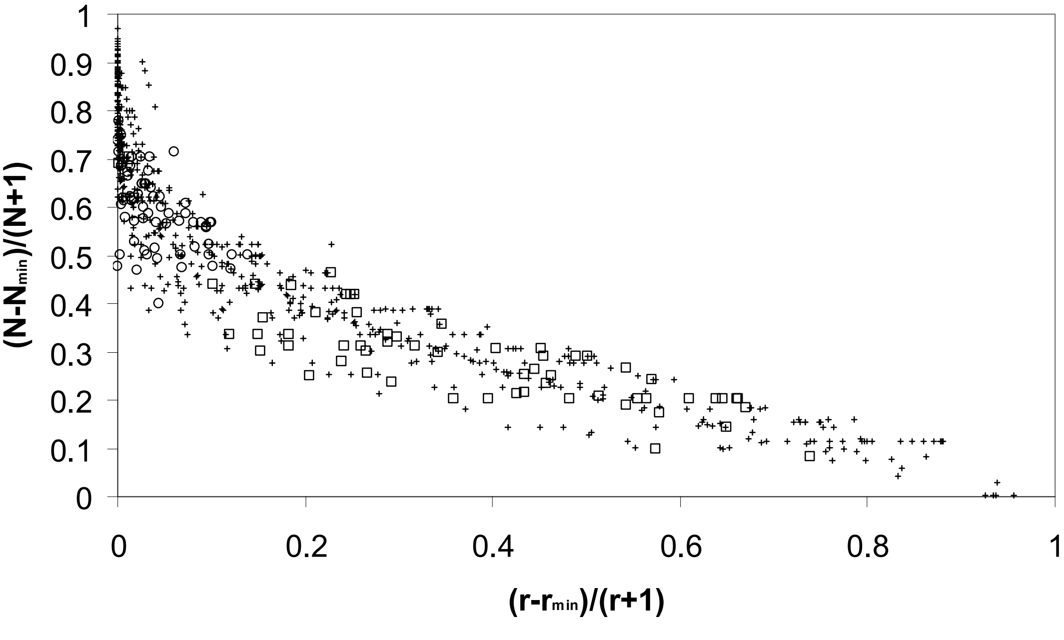

Figure 9- Gilliland graphic for all the evaluated points.

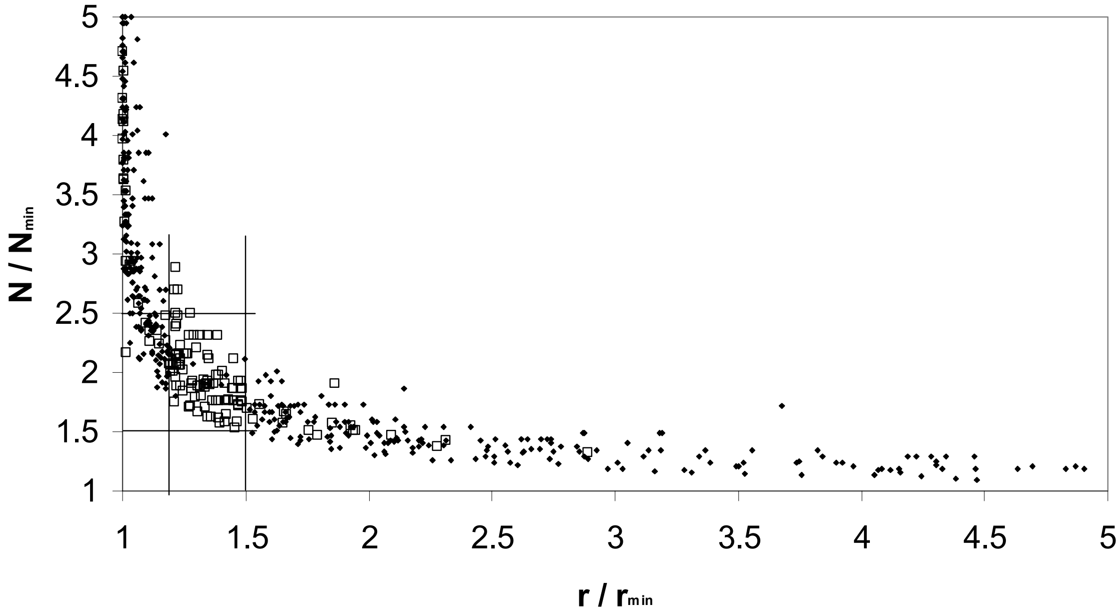

Figure 10- Proposed correlation for the number of stages and reflux.

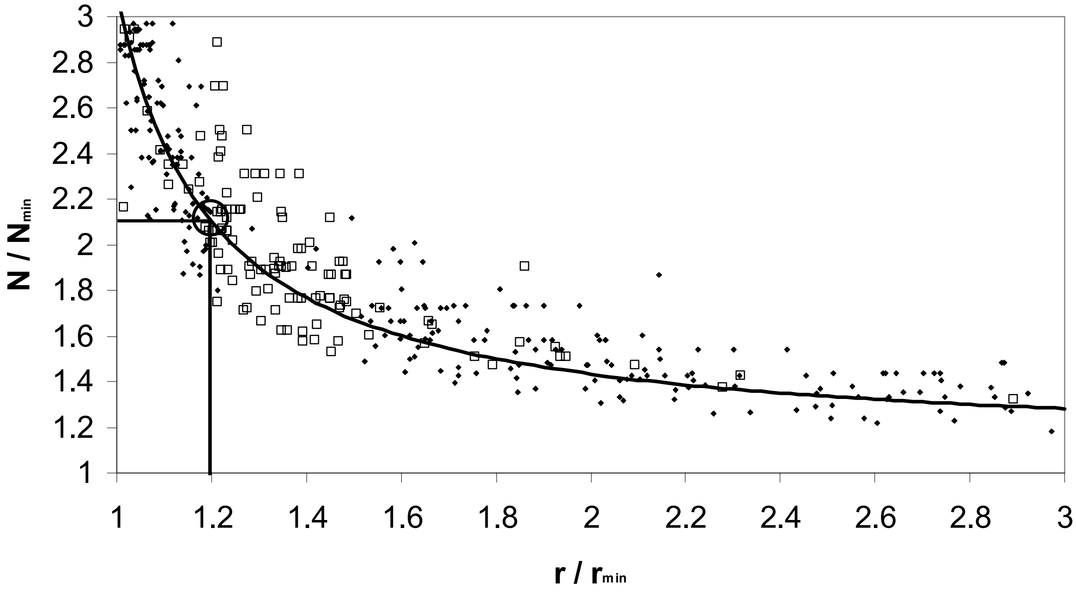

Figure 11- Adjustment of the proposed correlation.

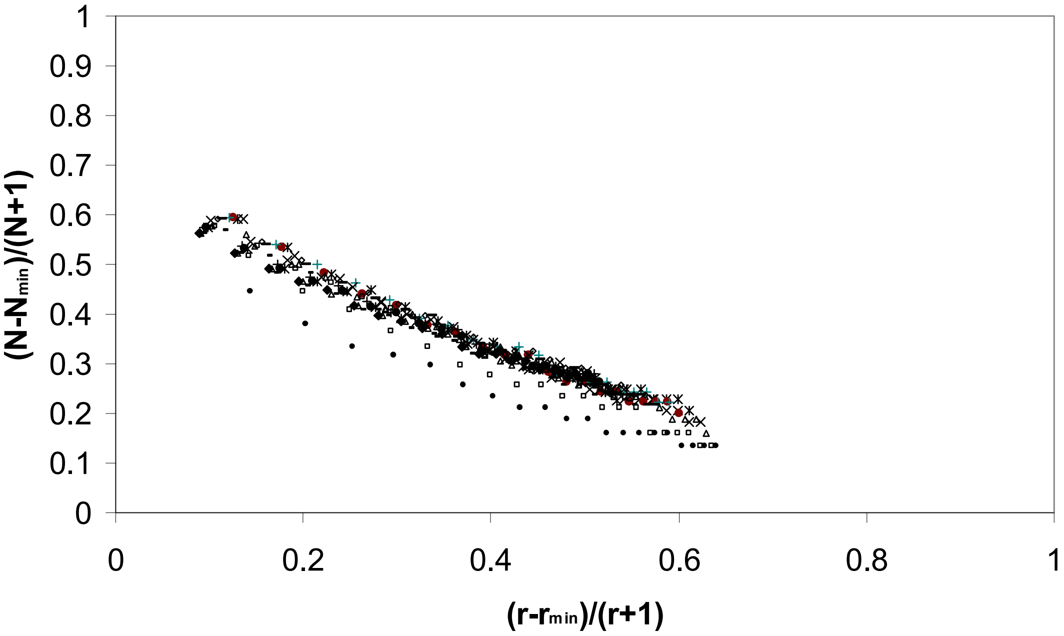

Figure 12- Gilliland's representation for a reactive distillation column.

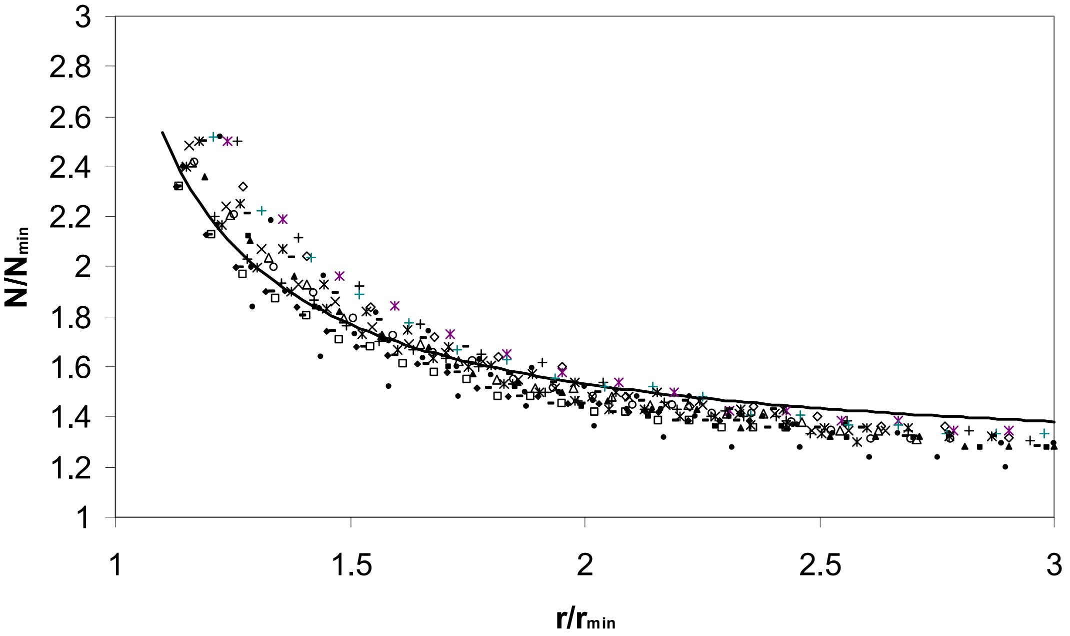

Figure 13- Representation for a reactive distillation column.

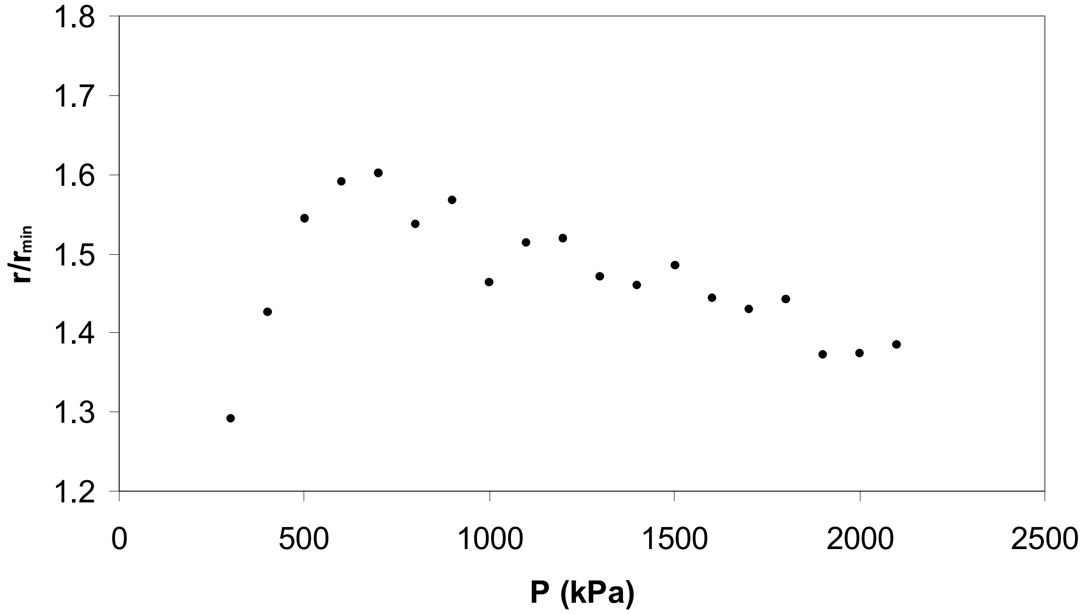

Figure 14 – Sensitivity analysis of the pressure of a reactive column on a reactive pressure swing distillation for $N/N_{min}=1.8$.

4. Conclusions

Gilliland covered all the feasible operation range with his graphic. A graphic where is more easily identificable the optimal operation zone is proposed with a correlation equation. The graphical representation of the quotients versus its minimal values of the number of stages and reflux show some advantages in front of Gilliland coordinates.

Our goal is not an accurate and universal correlation for the number of stages and reflux, but it is just to provide an initial orientation before to the detailed study of each particular case. The rule of thumb that the optimal reflux is from 1.2 to 1.5 its minimal value is verified. It is demonstrated that this heuristic is consequence of the number of stages in front of the reflux curve shape. The optimum is always at the elbow zone of the curve and these curves are independent of the energy and steel cost fluctuations. In order to minimize the carbon dioxide emissions, it would be recommendable to use the lower value factor of 1.2 at the first calculations of column design.

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Annex

Case	**Components**	**Quality**	**x_F**	**Case**	**Components**	**Quality**	**x_F**
Case I	Benzene	b.p.	0.50	Case IX	Phenol	b.p.	0.0011
(Gilliland)	Toluene	1 atm	0.50	(Gilliland)	o-Cresol	1 atm	0.2265
					m-Cresol		0.4630
					Xylenol		0.3092
Case II	Phenol	b.p.	0.35	Case X	o-Cresol	b.p.	0.003
(Gilliland)	o-Cresol	1 atm	0.15	(Gilliland)	m-Cresol	1 atm	0.598
	m-Cresol		0.30		Xylenol		0.399
	Xylenol		0.20				
Case III	Benzene	b.p.	0.60	Case XI	Ethane	b.p.	0.0584
(Gilliland)	Toluene	1 atm	0.30	(Gilliland)	Propane	20 atm	0.1890
	o-xylene		0.10		Butane		0.3840
					Pentane		0.2410
					Nonane		0.1280
Case IV	Methane	b.p.	0.020	Case XII	Propane	b.p.	0.150
(Gilliland)	Ethane	20 atm	0.100	(Gilliland)	n-butane	20 atm	0.300
	Propene		0.060		pentane		0.550
	Propane		0.125				
	Isobutene		0.035				
	n-butane		0.150				
	pentane		0.152				
	hexane		0.113				
	heptane		0.090				
	octane		0.085				
	decane		0.070				
Case V	Benzene	b.p.	0.55	Case XIII	Propane	b.p.	0.15
(Gilliland)	Toluene	1 atm	0.45	(Gilliland)	Butane	1 atm	0.30
					pentane		0.55
Case VI	Benzene	65 %	0.60	Case XIV	Pentane	b.p.	0.310
(Gilliland)	Toluene	vapor	0.40	(Gilliland)	Heptane	1 atm	0.266
		1 atm			Octane		0.187
					Nonane		0.125
					Decane		0.112
Case VII	Benzene	b.p.	0.45	Case XV	Hydrogen	68 %	0.17
(Gilliland)	Toluene	1 atm	0.35	(Gilliland)	Methane	vapor	0.28
	Xylene		0.20		Ethane	1 atm	0.25
					Ethane		0.12
					Propene		0.13
					Propane		0.03
					Butane		0.02
Case VIII	Phenol	b.p.	0.35	Case XVI	Methane	b.p.	0.0366
(Gilliland)	o-Cresol	1 atm	0.15	(Gilliland)	Ethane	20 atm	0.4212
	m-Cresol		0.30		Ethane		0.2122
	Xylenol		0.20		Propene		0.2382
					Propane		0.0552
					Butane		0.0366

	methanol	ethanol	acetone	water	P (atm)	quality
a.1; a.13	0	0.65	0	0.35	1	b.p.
a.14	0	0.60	0	0.40	1	b.p.
a.2; a.8; a.15	0	0.55	0	0.45	1	b.p.
a.3; a.9	0	0.45	0	0.50	1	b.p.
a.4; a.10	0	0.40	0	0.60	1	b.p.
a.5; a.11	0	0.35	0	0.65	1	b.p.
a.6; a.16	0	0.30	0	0.70	1	b.p.
a.7; a.12; a.17	0	0.65	0	0.35	1	b.p.
b.1	0.60	0.30	0	0.10	1	b.p.
b.2	0.50	0.30	0	0.20	1	b.p.
b.3	0.45	0.30	0	0.25	1	b.p.
b.4	0.40	0.30	0	0.30	1	b.p.
b.5	0.35	0.30	0	0.35	1	b.p.
b.6	0.30	0.30	0	0.40	1	b.p.
b.7	0.25	0.30	0	0.45	1	b.p.
b.8	0.55	0.35	0	0.10	1	b.p.
b.9	0.50	0.35	0	0.15	1	b.p.
b.10	0.45	0.35	0	0.20	1	b.p.
b.11	0.40	0.35	0	0.25	1	b.p.
b.12	0.35	0.35	0	0.30	1	b.p.
b.13	0.25	0.35	0	0.40	1	b.p.
b.14	0.20	0.35	0	0.45	1	b.p.
c.1	0.10	0	0.10	0.80	1	b.p.
c.2	0.10	0	0.10	0.80	1	b.p.
c.3	0.10	0	0.10	0.80	1	b.p.
c.4	0.10	0	0.10	0.80	1	b.p.
c.5	0.10	0	0.10	0.80	1	b.p.
c.6	0.10	0	0.10	0.80	1	b.p.
c.7	0.10	0	0.10	0.80	1	b.p.
c.8	0.10	0	0.10	0.80	1	b.p.
c.9	0.20	0	0.20	0.60	1	b.p.

Case	D/F	rmin	Nmin	Case	D/F	rmin	Nmin	Case	D/F	rmin	Nmin
I	0.5000	1.1667	7	a.1	0.8649	0.3143	5.6	b.1	0.6010	2.2397	21
I.1	0.6110	0.8776	7	a.2	0.7297	0.5660	5.6	b.2	0.5000	2.9300	21
I.2	0.7220	0.6338	7	a.3	0.6622	0.5969	5.6	b.3	0.4495	3.1303	21
I.3	0.8333	0.3671	7	a.4	0.5946	0.6058	5.6	b.4	0.3990	3.2255	21
I.4	0.8889	0.1777	7	a.5	0.5270	0.6104	5.6	b.5	0.3485	3.6678	21
I.5	0.9222	0.0126	7	a.6	0.4595	0.6167	5.6	b.6	0.2980	4.7619	21
I.6	0.3889	1.5699	7	a.7	0.3919	0.6180	5.6	b.7	0.2475	5.7490	21
I.7	0.2778	2.2221	7	a.8	0.7826	0.1681	4.7	b.8	0.5464	2.5274	17
I.8	0.1667	3.5144	7	a.9	0.7101	0.2713	4.7	b.9	0.4948	2.8084	17
I.9	0.0556	7.3943	7	a.10	0.6377	0.3323	4.7	b.10	0.4433	3.0458	17
II	0.3300	4.4065	21	a.11	0.5652	0.3684	4.7	b.11	0.3918	3.7866	17
III	0.6000	1.0169	12.4	a.12	0.4203	0.4188	4.7	b.12	0.3402	4.1229	17
IV	0.3161	0.2721	8	a.13	0.8571	0.3151	4.9	b.13	0.2371	5.8762	17
V	0.5556	1.0129	7.4	a.14	0.7857	0.4888	4.9	b.14	0.1856	7.8780	17
VI	0.6020	1.5238	11	a.15	0.7143	0.5660	4.9				
VII	0.4430	1.2939	10.1	a.16	0.4286	0.6094	4.9				
VIII	0.3527	5.8335	44.4	a.17	0.3571	0.5757	4.9	c.1	0.2063	0.7808	5.8
IX	0.2266	10.1169	38					c.2	0.2063	0.7806	5.8
X	0.6000	2.5180	21.2					c.3	0.2179	0.6423	5.3
XI	0.2764	0.8756	8					c.4	0.2308	0.4788	5.1
XII	0.2996	0.2340	8					c.5	0.2617	0.2061	4.4
XIII	0.3005	1.70	7.1					c.6	0.2806	0.0909	4.2
XIV	0.5778	1.78	5.5					c.7	0.3023	0.0283	3.7
XV	0.4534	0.18	1.8					c.8	0.2179	0.6257	5.3
XVI	0.4579	2.4	14.4					c.9	0.4413	0.3186	5.3

Case	r	N	Nalim	Case	r	N	Nalim
I	1.1700	30	15	I.5	0.0126	30	7
	1.2400	20	10		0.0127	20	4
	1.4700	15	8		0.0155	15	3
	1.7300	13	7		0.0271	13	3
	1.9800	12	6		0.0465	12	3
	2.3700	11	6		0.0933	11	3
	3.1800	10	6		0.2128	10	3
	5.0000	9	5		0.5779	9	3
	15.7800	8	5		2.9348	8	3
I.1	0.8809	30	16	I.6	1.5788	30	15
	0.9251	20	10		1.6812	20	10
	1.0819	15	7		1.9840	15	8
	1.2748	13	6		2.3342	13	7
	1.4478	12	6		2.6430	12	7
	1.7715	11	5		3.1875	11	6
	2.3215	10	5		4.1150	10	6
	3.8117	9	5		6.5712	9	6
	12.3504	8	4		20.2840	8	5
I.2	0.6351	30	15	I.7	2.2355	30	15
	0.6681	20	11		2.3738	20	11
	0.7508	15	7		2.7786	15	9
	0.8757	13	6		3.2174	13	8
	0.9976	12	5		3.6311	12	7
	1.2044	11	5		4.2638	11	7
	1.6583	10	4		5.5824	10	7
	2.6764	9	4		8.5413	9	6
	8.9277	8	4		25.9826	8	6
I.3	0.3673	30	14	I.8	3.5305	30	15
	0.3731	20	8		3.6939	20	11
	0.4108	15	6		4.1915	15	9
	0.4709	13	5		4.7933	13	8
	0.5402	12	4		5.2703	12	8
	0.6519	11	4		6.1608	11	8
	0.9918	10	3		7.7824	10	7
	1.6373	9	3		11.7373	9	7
	5.7177	8	3		35.7713	8	6
I.4	0.1777	30	10	I.9	7.3990	30	17
	0.1790	20	7		7.5081	20	13
	0.2030	14	4		8.0078	15	11
	0.2214	13	4		8.6852	13	10
	0.2633	12	4		9.4327	12	9
	0.3321	11	3		10.4797	11	9
	0.4865	10	3		13.0009	10	8
	0.9502	9	3		18.2988	9	8
	3.9123	8	3		54.0059	8	7

Case	r	N	Nalim
a.1	0.3140	30	9-18
	0.3150	22	9
	0.3160	20	10
	0.3190	17	7
	0.3240	15	7
	0.3360	13	6
	0.3470	12	5
	0.3680	11	5
	0.4040	10	4
	0.4630	9	4
	0.6090	8	4
	0.9850	7	3
	3.2796	6	3
a.2	0.5665	50	30-38
	0.5665	48	26-38
	0.5665	46	29-36
	0.5665	44	24-36
	0.5665	42	24-35
	0.5676	36	26
	0.5678	32	22
	0.5686	30	22
	0.5695	28	20
	0.5710	26	19
	0.5730	24	17
	0.5760	22	15
	0.5803	20	14
	0.5876	18	12
	0.5998	16	11
	0.6082	15	10
	0.6204	14	9
	0.6394	13	8
	0.6637	12	8
	0.6985	11	7
	0.7610	10	6
	0.8709	9	6
	1.0666	8	5
	1.6547	7	4
	4.9919	6	4
a.3	0.5990	44	31-39
	0.6003	40	35
	0.6044	30	24
	0.6223	20	15
	0.6486	18	12
	0.6746	14	10
	0.6971	13	9
	0.7291	12	8
	0.7749	11	8
	0.8397	10	7
	0.9558	9	6
	1.2025	8	5
	1.8197	7	5
	5.4501	6	4
a.4	0.6138	40	36
	0.6213	30	26
	0.6241	28	24
	0.6275	26	22
	0.6321	24	20
	0.6381	22	18
	0.6424	21	17
	0.6468	20	16
	0.6594	18	14
	0.6792	16	12
	0.7134	14	10
	0.7379	13	10
	0.7702	12	9
	0.8177	11	8
	0.8962	10	7
	1.0368	9	6
	1.2996	8	6
	1.9302	7	5
	6.0736	6	4
a.5	0.6160	50	44
	0.6253	34	30
	0.6524	22	18
	0.7378	14	11
	0.8018	12	9
	0.9482	10	7
	1.3585	8	6
	2.0560	7	5
	6.8016	6	4

Case	r	N	Nalim	Case	r	N	Nalim
a.6	0.6178	50	48	a.9	0.2717	20	10-18
	0.6242	40	36		0.2718	15	11
	0.6372	30	27		0.2748	11	9
	0.6752	20	17		0.3031	10	5
	0.6918	18	15		0.3221	9	5
	0.7557	14	11		0.3675	8	4
	0.7857	13	10		0.4625	7	4
	0.8291	12	9		0.7969	6	3
	0.8945	11	8		3.2022	5	3
	0.9861	10	8				
	1.1320	9	7				
	1.4200	8	6				
	2.1929	7	5				
	7.0776	6	5				
a.7	0.6422	30	26	a.10	0.3323	100	30-50
	0.6475	28	24		0.3323	90	25-31
	0.6586	20	17		0.3323	80	25-40
	0.6837	18	16		0.3323	70	21-36
	0.7499	15	12		0.3322	50	20-40
	1.0168	10	8		0.3321	40	15-30
	0.9236	11	9		0.3323	30	18-22
	1.1749	9	7		0.3328	25	11-19
	1.4913	8	6		0.3339	20	13
	0.8569	12	9		0.3344	19	13
	2.3607	7	5		0.3360	17	11
	7.3086	6	5		0.3390	15	10
					0.3529	12	7
					0.3616	11	7
					0.3776	10	6
					0.4099	9	5
					0.4593	8	5
					0.5769	7	4
					0.9548	6	4
					3.8846	5	3
a.8	0.1676	30	9-16	a.11	0.3699	20	14
	0.1684	20	8-11		0.3721	18	13
	0.1693	15	7		0.3759	16	11
	0.1742	12	5		0.3835	14	10
	0.1780	11	5		0.3963	12	8
	0.1863	10	4		0.4338	10	6
	0.1984	9	4		0.5237	8	5
	0.2340	8	4		0.6869	7	4
	0.3090	7	3		1.0566	6	4
	0.5349	6	3		4.6464	5	3
	2.6300	5	3				

Case	r	N	Nalim	Case	r	N	Nalim
a.12	0.4194	30	20-25	a.15	0.5707	25	18
	0.4206	25	19		0.5727	23	17
	0.4244	20	15		0.5756	21	15
	0.4383	15	11		0.5807	19	14
	0.4686	12	9		0.5880	17	12
	0.5125	10	7		0.6006	15	11
	0.6633	8	5		0.6219	13	9
	0.8277	7	5		0.6419	12	8
	1.3361	6	4		0.6732	11	8
	5.6043	5	4		0.7105	10	7
					0.7782	9	6
					0.9164	8	5
					1.1674	7	5
					1.9826	6	4
					23.6902	5	4
a.13	0.3150	35	10-25	a.16	0.6221	40	37
	0.3150	30	9-20		0.6339	30	27
	0.3164	20	9		0.6454	25	22
	0.3773	10	5		0.6727	20	16
	0.4161	9	4		0.6822	18	16
	0.4933	8	4		0.7026	14	14
	0.6985	7	4		0.7026	16	14
	1.2507	6	3		0.7877	12	10
	16.8553	5	3		0.8970	10	8
					1.0040	9	7
					1.1738	8	7
					1.5097	7	6
					2.5331	6	5
					28.6950	5	4
a.14	0.4890	45	15-36	a.17	0.6176	60	56
	0.4890	40	15-31		0.6217	50	46
	0.4890	35	16-25		0.6283	40	37
	0.4887	30	21		0.6409	30	27
	0.4887	28	18		0.6779	20	18
	0.4890	25	15		0.7339	15	13
	0.4921	20	13		0.8139	12	10
	0.4952	18	11		0.8627	11	9
	0.5055	15	9		0.9378	10	8
	0.5343	12	7		1.0405	9	8
	0.5880	10	6		1.2140	8	7
	0.7496	8	5		1.5771	7	6
	0.9819	7	4		2.7020	6	5
	1.7071	6	4		34.6644	5	5
	21.5012	5	3				

Case	r	N	Nalim	Case	r	N	Nalim
b.1	2.2552	80	48	b.5	3.6678	250	124
	2.5936	50	28		3.6678	150	63
	3.1670	40	21		3.6680	200	83
	3.8525	35	18		3.6698	100	40
	5.4975	30	15		3.8406	60	27
					4.1624	50	23
					4.4919	45	21
					5.0504	40	19
					6.0997	35	17
					8.4859	30	16
					10.4660	28	15
					17.7051	25	14
b.2	2.9543	60	29	b.6	4.8500	70	28
	2.9916	55	28		4.9200	65	26
	3.1276	50	25		5.1000	60	25
	3.3562	45	23		5.1700	55	23
	3.7492	40	20		5.4000	50	22
	4.5012	35	18		5.7800	45	21
	6.2081	30	15		6.4200	40	19
	13.0723	25	13		7.6100	35	17
					10.2700	30	16
					12.5200	28	15
					16.7700	26	15
					20.6132	25	14
b.3	3.1670	70	33	b.7	48.0683	23	14
	3.2505	60	29		31.5888	24	14
	3.4964	50	24		19.4740	26	15
	3.7528	45	22		14.7022	28	16
	4.2000	40	20		13.2300	29	16
	5.0300	35	17		12.1276	30	16
	6.9000	30	15		9.0762	35	18
	8.6000	28	14		7.7194	45	19
	11.7000	26	14		6.2757	55	23
	14.5000	25	13		23.8755	25	15
					5.8951	70	26
					5.8098	80	28
b.4	3.2681	70	33	b.8	2.5274	100	57
	3.3636	60	28		2.5348	70	40
	3.6376	50	24		2.6229	50	28
	3.9324	45	21		2.8475	40	22
	4.4229	40	20		3.1169	35	19
	5.3498	35	17		3.6649	30	16
	5.9709	33	17		5.0363	25	14
	7.4684	30	15				
	8.2336	29	15				
	12.6438	26	14				
	15.8146	25	13				

Case	r	N	Nalim
b.9	2.8373	60	32
	2.8638	55	29
	2.9114	50	27
	3.0003	45	24
	3.1625	40	22
	3.4621	35	19
	4.0725	30	16
	5.5907	25	14
b.10	3.0462	100	50
	3.1681	50	26
	3.4701	40	21
	4.0577	33	18
	5.0743	28	15
	6.3803	25	14
	8.0970	23	13
	11.8693	21	12
	16.1555	20	12
b.11	3.7865	120	52
	3.7865	150	81
	3.7874	100	50
	3.7920	80	39
	3.8037	70	33
	3.8456	60	30
	3.8889	55	27
	3.9683	50	25
b.12	4.1368	70	31
	4.1706	60	28
	4.2766	50	24
	4.3993	45	22
	4.6215	40	20
	5.0321	35	18
	5.8595	30	16
	6.8063	27	15
	7.9050	25	14
	8.6791	24	14
b.13	5.8857	80	32
	5.8926	75	30
	5.9038	70	29
	5.9523	60	26
	6.0946	50	23
	6.5198	40	20
	7.0213	35	19
	8.0200	30	17
	10.5425	25	15
	14.7405	22	14
	17.6796	21	13
b.14	7.8862	90	32
	7.8988	80	30
	7.9315	70	28
	8.0095	60	26
	8.2177	50	23
	8.8049	40	20
	9.4775	35	19
	10.8876	30	18
	12.5863	27	17
	14.5579	25	16
	16.1034	25	16

Case	r	N	Nalim	Case	r	N	Nalim
c.1	0.7808	29	15	c.2	0.7807	100	40
	0.7809	28	15		0.7807	90	40
	0.7810	27	14		0.7807	60	47
	0.7812	26	14		0.7807	80	17
	0.7813	25	13		0.7807	50	20
	0.7816	24	13		0.7807	40	20
	0.7821	23	12		0.7807	70	17
	0.7828	22	12		0.7808	30	15
	0.7840	21	11		0.7808	29	1
	0.7858	20	11		0.7809	28	15
	0.7891	19	10		0.7810	27	14
	0.7931	18	10		0.7812	26	14
	0.8020	17	9		0.7813	25	13
	0.8109	16	9		0.7816	24	13
	0.8315	15	9		0.7820	23	12
	0.8533	14	8		0.7828	22	12
	0.8992	13	8		0.7840	21	1
	0.9543	12	7		0.7858	20	11
	1.0600	11	7		0.7891	19	1
	1.2155	10	6		0.7931	18	10
	1.5034	9	6		0.8020	17	9
	2.1697	8	5		0.8109	16	9
	3.8021	7	5		0.8315	15	9
	27.6258	6	5		0.8533	14	8
					0.8991	13	1
					1.0041	12	8
					1.0944	11	6
					1.2155	10	6
c.3	0.7636	11	6	c.4	0.4804	18	8
	0.8455	10	5		0.4868	15	7
	0.9676	9	5		0.5818	10	5
	1.2522	8	5		0.6652	9	4
	1.8572	7	4		0.7898	8	4
	3.7260	6	4		1.0906	7	4
					1.9718	6	4

Case	r	N	Nalim	Case	r	N	Nalim
c.5	0.2063	20	7	c.6	0.0909	60	29
	0.2079	15	5		0.0909	50	24
	0.2421	10	4		0.0909	30	13
					0.0909	40	23
					0.0910	20	7
					0.1106	10	3
					0.1691	8	2
					0.4867	6	2
					1.2067	5	3
c.7	0.0283	25	20	c.8	0.6273	20	10
	0.0283	12	7		0.6297	18	9
	0.0283	20	15		0.6357	16	8
	0.0283	40	35		0.6516	14	7
	0.0287	8	3		0.6941	12	6
	0.2818	6	3		0.8174	10	5
	0.2818	7	3		1.2110	8	5
	0.8181	5	3		3.5461	6	4
	5.2816	4	3				
c.9	0.3128	50	39				
	0.3134	20	11				
	0.3186	15	8				
	0.3821	10	5				
	0.5492	8	4				
	0.8210	7	4				
	1.9301	6	4				

P (kPa)	D/F	xF (RD – reactive distillation)			
		MeAc	EtOH	EtAc	MeOH
301.325	0.9511	0.630	0.049	0.000	0.322
401.325	0.9190	0.608	0.081	0.000	0.311
501.325	0.8947	0.592	0.105	0.000	0.302
601.325	0.8750	0.579	0.125	0.000	0.296
701.325	0.8583	0.568	0.142	0.000	0.290
801.325	0.8437	0.558	0.156	0.000	0.285
901.325	0.8308	0.550	0.169	0.000	0.281
1001.325	0.8192	0.542	0.181	0.000	0.277
1101.325	0.8087	0.535	0.191	0.000	0.273
1201.325	0.7990	0.529	0.201	0.000	0.270
1301.325	0.7901	0.523	0.210	0.000	0.267
1401.325	0.7817	0.517	0.218	0.000	0.264
1501.325	0.7740	0.512	0.226	0.000	0.262
1601.325	0.7667	0.507	0.233	0.000	0.259
1701.325	0.7598	0.503	0.240	0.000	0.257
1801.325	0.7533	0.499	0.247	0.000	0.255
1901.325	0.7472	0.495	0.253	0.000	0.253
2001.325	0.7414	0.491	0.259	0.000	0.251
2101.325	0.7358	0.487	0.264	0.000	0.249

Case	r	N	Nalim
RD	1.77	46	29
	1.97	41	25
P= 301.325 kPa	2.17	38	22
	2.37	37	21
xB (MeAc)= 0.99	2.57	36	20
	2.77	34	19
xD (EtAc+EtOH)=	2.97	33	18
7.76E-05	3.17	32	17
	3.37	32	17
rmin= 1.37	3.57	31	16
Nmin= 25	3.77	31	16
	3.97	30	15
	4.17	30	15
	4.37	30	15
	4.57	30	15
	4.77	30	15
	4.97	29	14
	5.17	29	14
	5.37	29	14
	5.57	29	14

Case	r	N	Nalim
RD	1.81	53	35
	2.01	46	30
P= 401.325 kPa	2.21	43	27
	2.41	40	24
xB (MeAc)= 0.99	2.61	38	23
	2.81	36	21
xD (EtAc+EtOH)= 1.33E-04	3.01	35	20
	3.21	34	19
	3.41	34	19
rmin= 1.41	3.61	33	18
Nmin= 25	3.81	33	18
	4.01	32	17
	4.21	32	17
	4.41	32	17
	4.61	30	16
	4.81	30	16
	5.01	30	16
	5.21	30	16
	5.41	29	15
	5.61	29	15
RD	1.87	58	41
	2.07	51	34
P= 501.325 kPa	2.27	46	30
	2.47	43	27
xB (MeAc)= 0.99	2.67	41	25
	2.87	40	24
xD (EtAc+EtOH)= 1.78E-04	3.07	37	22
	3.27	36	21
	3.47	36	21
rmin= 1.47	3.67	35	20
Nmin= 25	3.87	34	19
	4.07	34	19
	4.27	33	18
	4.47	33	18
	4.67	33	18
	4.87	32	17
	5.07	31	17
	5.27	31	17
	5.47	31	17
	5.67	30	16

Case	r	N	Nalim
RD	1.94	65	47
	2.14	55	38
P= 601.325 kPa	2.34	50	33
	2.54	46	30
xB (MeAc)= 0.99	2.74	43	27
	2.94	42	26
xD (EtAc+EtOH)= 2.16E-04	3.14	40	24
	3.34	38	23
	3.54	37	22
rmin= 1.54	3.74	36	21
Nmin= 26	3.94	36	21
	4.14	35	20
	4.34	35	20
	4.54	34	19
	4.74	34	19
	4.94	34	19
	5.14	33	18
	5.34	33	18
	5.54	32	18
	5.74	32	18
RD	2.08	65	47
	2.28	57	39
P= 701.325 kPa	2.48	51	34
	2.68	48	31
xB (MeAc)= 0.99	2.88	45	29
	3.08	43	27
xD (EtAc+EtOH)= 2.50E-04	3.28	41	25
	3.48	40	24
	3.68	39	23
rmin= 1.68	3.88	37	22
Nmin= 26	4.08	37	22
	4.28	36	21
	4.48	36	21
	4.68	35	20
	4.88	35	20
	5.08	35	20
	5.28	34	19
	5.48	34	19
	5.68	34	19
	5.88	33	18

Case	r	N	Nalim
RD	2.2	68	49
	2.4	59	41
P= 801.325 kPa	2.6	53	36
	2.8	49	32
xB (MeAc)= 0.99	3	47	30
	3.2	44	28
xD (EtAc+EtOH)=	3.4	43	27
2.80E-04	3.6	41	25
	3.8	40	24
rmin= 1.8	4	40	24
Nmin= 27	4.2	38	23
	4.4	37	22
	4.6	37	22
	4.8	36	21
	5	36	21
	5.2	35	20
	5.4	35	20
	5.6	35	20
	5.8	35	20
	6	34	19
RD	2.32	68	49
	2.52	60	42
P= 901.325 kPa	2.72	55	37
	2.92	51	34
xB (MeAc)= 0.99	3.12	48	31
	3.32	45	29
xD (EtAc+EtOH)=	3.52	44	28
3.08E-04	3.72	42	26
	3.92	41	25
rmin= 1.92	4.12	41	25
Nmin= 27	4.32	40	24
	4.52	38	23
	4.72	38	23
	4.92	37	22
	5.12	37	22
	5.32	36	21
	5.52	36	21
	5.72	36	21
	5.92	35	20
	6.12	35	20

Case	r	N	Nalim
RD	2.5	66	47
	2.7	59	41
P= 1001.325 kPa	2.9	55	37
	3.1	51	34
xB (MeAc)= 0.99	3.3	48	31
	3.5	47	30
xD (EtAc+EtOH)=	3.7	44	28
3.33E-04	3.9	43	27
	4.1	42	26
rmin= 2.1	4.3	41	25
Nmin= 28	4.5	40	24
	4.7	40	24
	4.9	38	23
	5.1	38	23
	5.3	37	22
	5.5	37	22
	5.7	37	22
	5.9	36	21
	6.1	36	21
	6.3	36	21
RD	2.54	70	51
	2.74	62	44
P= 1101.325 kPa	2.94	57	39
	3.14	53	36
xB (MeAc)= 0.99	3.34	50	33
	3.54	48	31
xD (EtAc+EtOH)=	3.74	47	30
3.57E-04	3.94	44	28
	4.14	43	27
rmin= 2.14	4.34	42	26
Nmin= 28	4.54	41	25
	4.74	41	25
	4.94	40	24
	5.14	40	24
	5.34	38	23
	5.54	38	23
	5.74	37	22
	5.94	37	22
	6.14	37	22
	6.34	36	21

Case	r	N	Nalim
RD	2.65	70	51
	2.85	63	44
P= 1201.325 kPa	3.05	58	40
	3.25	54	36
xB (MeAc)= 0.99	3.45	51	34
	3.65	49	32
xD (EtAc+EtOH)=	3.85	47	30
3.80E-04	4.05	45	29
	4.25	44	28
rmin= 2.25	4.45	43	27
Nmin= 28	4.65	42	26
	4.85	42	26
	5.05	41	25
	5.25	40	24
	5.45	40	24
	5.65	38	23
	5.85	38	23
	6.05	38	23
	6.25	37	22
	6.45	37	22
RD	2.76	70	51
	2.96	64	45
P= 1301.325 kPa	3.16	58	40
	3.36	55	37
xB (MeAc)= 0.99	3.56	52	35
	3.76	50	33
xD (EtAc+EtOH)=	3.96	48	31
4.01E-04	4.16	47	30
	4.36	45	29
rmin= 2.36	4.56	44	28
Nmin= 29	4.76	43	27
	4.96	42	26
	5.16	42	26
	5.36	41	25
	5.56	41	25
	5.76	40	24
	5.96	39	24
	6.16	38	23
	6.36	38	23
	6.56	38	23

Case	r	N	Nalim
RD	2.86	70	51
	3.06	64	45
P= 1401.325 kPa	3.26	59	41
	3.46	56	38
xB (MeAc)= 0.99	3.66	52	35
	3.86	50	33
xD (EtAc+EtOH)=	4.06	49	32
4.22E-04	4.26	47	30
	4.46	45	29
rmin= 2.46	4.66	44	28
Nmin= 29	4.86	44	28
	5.06	43	27
	5.26	42	26
	5.46	42	26
	5.66	41	25
	5.86	41	25
	6.06	40	24
	6.26	39	24
	6.46	39	24
	6.66	38	23
RD	2.96	72	52
	3.16	65	46
P= 1501.325 kPa	3.36	60	42
	3.56	56	38
xB (MeAc)= 0.99	3.76	54	36
	3.96	51	34
xD (EtAc+EtOH)=	4.16	49	32
4.41E-04	4.36	48	31
	4.56	47	30
rmin= 2.56	4.76	45	29
Nmin= 29	4.96	44	28
	5.16	43	27
	5.36	43	27
	5.56	42	26
	5.76	42	26
	5.96	41	25
	6.16	41	25
	6.36	39	24
	6.56	39	24
	6.76	39	24

Case	r	N	Nalim
RD	3.06	72	52
	3.26	65	46
P= 1601.325 kPa	3.46	60	42
	3.66	57	39
xB (MeAc)= 0.99	3.86	55	37
	4.06	52	35
xD (EtAc+EtOH)=	4.26	50	33
4.60E-04	4.46	49	32
	4.66	48	31
rmin= 2.66	4.86	46	30
Nmin= 30	5.06	45	29
	5.26	44	28
	5.46	43	27
	5.66	43	27
	5.86	42	26
	6.06	42	26
	6.26	41	25
	6.46	41	25
	6.66	40	25
	6.86	39	24
RD	3.15	72	52
	3.35	65	46
P= 1701.325 kPa	3.55	60	42
	3.75	57	39
xB (MeAc)= 0.99	3.95	55	37
	4.15	52	35
xD (EtAc+EtOH)=	4.35	51	34
4.78E-04	4.55	49	32
	4.75	48	31
rmin= 2.75	4.95	47	30
Nmin= 30	5.15	45	29
	5.35	45	29
	5.55	44	28
	5.75	43	27
	5.95	43	27
	6.15	42	26
	6.35	42	26
	6.55	42	26
	6.75	41	25
	6.95	40	25

Case	r	N	Nalim
RD	3.24	72	52
	3.44	66	47
P= 1801.325 kPa	3.64	61	43
	3.84	58	40
xB (MeAc)= 0.99	4.04	56	38
	4.24	53	36
xD (EtAc+EtOH)=	4.44	51	34
4.95E-04	4.64	50	33
	4.84	49	32
rmin= 2.84	5.04	48	31
Nmin= 30	5.24	46	30
	5.44	45	29
	5.64	44	28
	5.84	44	28
	6.04	43	27
	6.24	43	27
	6.44	42	26
	6.64	42	26
	6.84	42	26
	7.04	40	25
RD	3.34	72	52
	3.54	66	47
P= 1901.325 kPa	3.74	61	43
	3.94	58	40
xB (MeAc)= 0.99	4.14	56	38
	4.34	53	36
xD (EtAc+EtOH)=	4.54	52	35
5.11E-04	4.74	50	33
	4.94	49	32
rmin= 2.94	5.14	48	31
Nmin= 31	5.34	46	30
	5.54	46	30
	5.74	45	29
	5.94	44	28
	6.14	44	28
	6.34	43	27
	6.54	43	27
	6.74	42	26
	6.94	42	26
	7.14	42	26

Case	r	N	Nalim
RD	3.42	72	52
	3.62	66	47
P= 2001.325 kPa	3.82	62	44
	4.02	59	41
xB (MeAc)= 0.99	4.22	56	38
	4.42	54	37
xD (EtAc+EtOH)=	4.62	52	35
5.27E-04	4.82	51	34
	5.02	50	33
rmin= 3.02	5.22	49	32
Nmin= 31	5.42	47	31
	5.62	46	30
	5.82	45	29
	6.02	45	29
	6.22	44	28
	6.42	44	28
	6.62	43	27
	6.82	43	27
	7.02	43	27
	7.22	42	26
RD	3.51	72	52
	3.71	66	47
P= 2101.325 kPa	3.91	62	44
	4.11	59	41
xB (MeAc)= 0.99	4.31	57	39
	4.51	54	37
xD (EtAc+EtOH)=	4.71	52	35
5.43E-04	4.91	51	34
	5.11	50	33
rmin= 3.11	5.31	49	32
Nmin= 31	5.51	47	31
	5.71	46	30
	5.91	46	30
	6.11	45	29
	6.31	45	29
	6.51	44	28
	6.71	44	28
	6.91	43	27
	7.11	43	27
	7.31	43	27