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Analysis and Modeling of Vapor Recompressive Distillation Using ASPEN-HYSYS

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Abstract: HYSYS process modeling software was used to analyze the effect of reflux ratio and number of trays on the purity of ethylene in a vapor recompression distillation column and also in an ordinary distillation column. Analysis of data showed that with increased pressure a higher reflux ratio is needed to obtain a purity of 99.9% for both towers. In addition number of trays was varied to see its effect on purity. Analysis proved that purity increases with number of trays.

Keywords: High Purity Ethylene, Recompressive Distillation, Ordinary Distillation, HYSYS Modeling

1 Introduction

Distillation is a process in which liquids are separated based on their relative volatilities and boiling points. The relative volatility of a substance is the measure of the ability to separate two components in the system [1]. This number indicates how easy or difficult a particular separation is. For example if the relative volatility of two components is close to one, the separation will be difficult. This is also an indication that the two components have very similar vapor pressure characteristics. In the case of ethane/ethylene binary system separation is considered somewhat difficult because the relative volatility is 1.2 at a feed temperature of -22.3°C and feed pressure of 2000 kPa.

Ethylene is an organic compound with the formula C_2H_4 and is considered one of the simplest and most important alkenes. It is a raw material used to make polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC) as well as making fibers and other organic materials. It is a building block chemical and usually the first organic compound that is

produced by a developing country when in shifts from being primarily an exporter of fuels to a manufacturer of intermediates and some finished products. These products can be used in other markets such as construction, electrical, as well as consumer chemical products such as coatings and adhesives [2]. Pure ethylene is important in the production of all of these products as well as the production of the compound ethylene oxide, which is then used to create ethylene glycol [2].

Ethylene and ethane separation can be conducted through various means including ordinary distillation, mechanical vapor recompression, and carbonized polyimide membranes. The most common and the basis for 100 billion kgs per year is ordinary distillation.

2 Study Cases

In this study the separation of ethylene and ethane separation was based on comparing two methods of separation, ordinary distillation (OD) and mechanical vapor recompression (VRC).

Ethylene and ethane separation can be conducted through various means including ordinary distillation which includes a condenser and reboiler with the tower traffic generated by external utilities. In vapor recompression, distillation involves the use of a compressor to recycle the latent heat from the overhead and recompressing it to conditions that are suitable to drive the reboiler at the bottom of the distillation tower. The purpose of this is to reduce the energy input to the tower by eliminating, or greatly reducing the outside utility consumption [3]. Sketches on the two systems are presented in the Appendix .

For both of these cases, studies were done by varying reflux ratio for pressures of 200, 1000, and 2000 kPa systems. The change in purity of ethylene was observed for each case and compared for both the ordinary distillation system and vapor recompression distillation systems. Along with reflux ratios, an equilibrium stage analysis, also known as a tray analysis was also conducted to determine how the number of trays affects purity.

3 Methodology

Aspen-HYSYS software is a general process simulation software available in the Research and Learning Center of Manhattan College. This software package is the used around the world to design plants and to rate

their performance. HYSYS was used to conduct the analysis on ordinary distillation and vapor recompression systems. Various pressures were set for both systems and reflux ratio and tray analysis were conducted in order to determine how results varied depending on pressure differences. Results were gathered and inputted into Microsoft Excel to observe trends in data.

4 Results

In this section, the results obtained from the analysis of VRC and OD distillation towers are presented and analyzed. The purity of ethylene for various pressures ranging from the 200 kPa and 2000 kPa pressure cases were used to determine how pressure and reflux ratio affected final purity. In addition, comparisons have been carried out between the results from vapor recompression distillation system and the ordinary distillation system.

4.1 Reflux Ratio Analysis:

An analysis was completed comparing the results from HYSYS process modeling software on a vapor recompression distillation tower and an ordinary distillation tower. Based on the results seen in Table 1 and 2, with increased pressure a higher reflux ratio is needed to obtain 99.9% purity of ethylene. This is because the relative volatility is higher at lower pressures so as the pressure increases more liquid needs to be refluxed to maintain the purity of the exiting product. In Figure 1 relative volatility is plotted against pressure. The figure suggests a negative correlation with relative volatility and pressure which suggests that decreasing pressure makes the light key significantly more volatile making the separation much easier.

Table 1. Ordinary Distillation Reflux Ratio Analysis Results

Tower Pressure	Overhead Ethylene	Overhead Ethane	Bottoms Ethylene	Bottoms Ethane	Condenser Duty	Reboiler Duty
kPa	mol %	ppm	ppm	mol %	kJ/h	kJ/h
2000	99.94	600	300	99.92	2.63E+07	2.64E+07
1000	99.9	978	1400	99.87	2.45E+07	2.46E+07
200	99.999	32	47	99.995	2.13E+07	2.14E+07

Table 2. Vapor Recompression Distillation Reflux Ratio Analysis Results

VRC	Ethylene	Ethane	HeatX Duty [kJ/hr]	Tube Side Delta T [C]	Shell Side Delta T [C]	Cooler Duty [kJ/hr]	Delta T [C]	Delta P [C]	Compressor Duty [kJ/hr]
2000	0.997	0.003	2.80E+07	7.34E-03	-1.12E+01	4.51E+06	-13.84	20	6.56E+06
1000	1	0.00E+00	3.58E+07	7.49E-01	-3.18E+00	4.59E+06	-22.59	20	5.85E+06
200	0.995	5.00E-03	2.01E+07	1.15E-01	-6.34E-01	2.32E+06	-33.81	0	3.22E+06

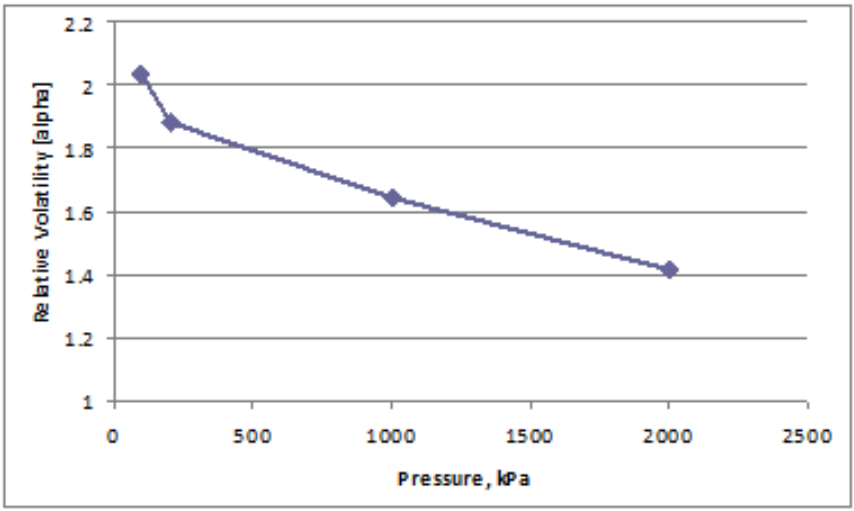

Figure 1. [4] Relative Volatility vs. Pressure

The individual HYSYS models are shown in Figures 2, 3 and 4. In VRC distillation, Figure 4, the bottoms is vaporized by exchanging heat from the top of the distillation column at the condenser [3]. After the fluid is recompressed the working fluid heat is exchanged at the reboiler. This system has proven to be much more efficient compared to the ordinary distillation tower. As seen in Table 1 and 2, the duties in OD are at a factor of 10^7 where as the duties in VRC are at a factor of 10^6. Even when pressure is steadily increased, with poorer volatilities, the vapor recompression system has still proven to be much more efficient compared to the ordinary distillation tower. This is because in an ordinary distillation tower, high pressure steam, or at best recuperated refrigerant is

used as the reboilers heat source and expensive refrigerant is used for the condensing. As a result, most of the heat is lost as low-grade energy in the process of condensing the overhead vapors [3].

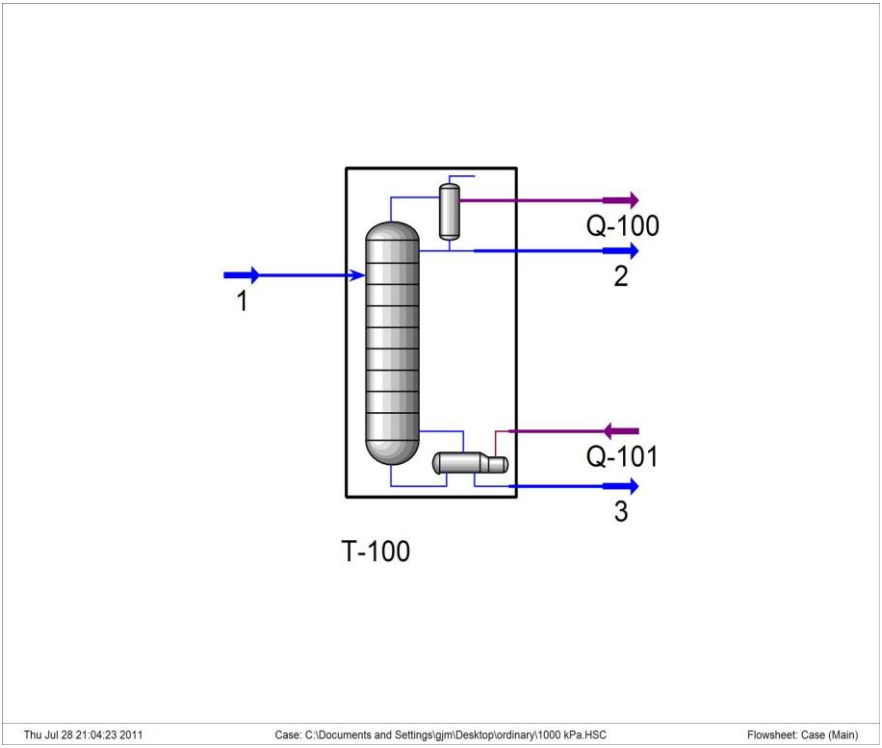

Figure 2. HYSYS Flow Diagram: Conventional Distillation

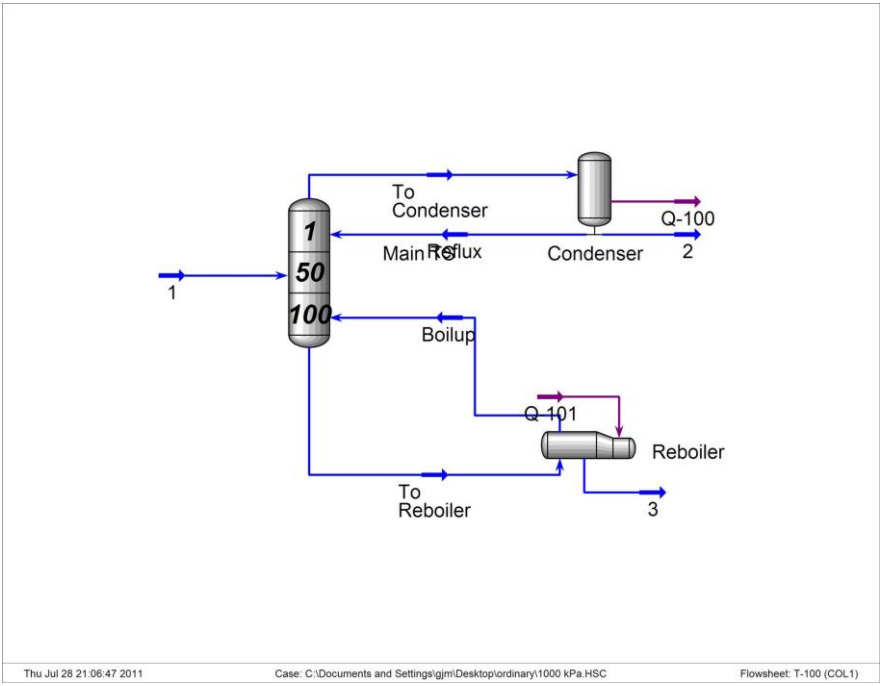

Figure 3. HYSYS Flow Diagram: Conventional Distillation – Sub-Flowsheet or Column Environment

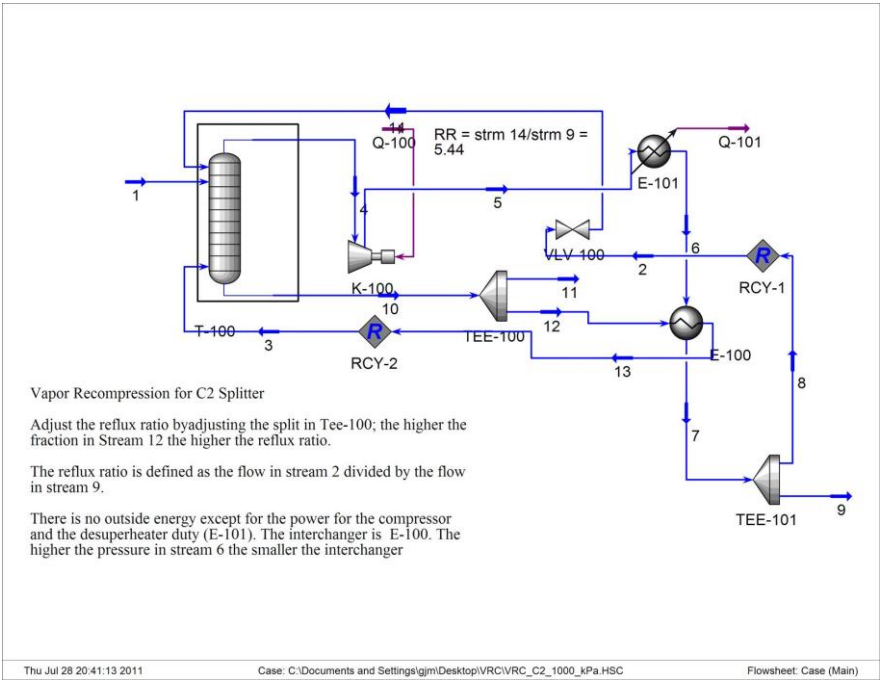

Figure 4. HYSYS Flow Diagram: Vapor Recompressive Distillation

In order to maintain a specific purity, a higher amount of reflux is needed as discussed in the previous section. Besides reflux ratio, the number of stages can also be manipulated to maintain purity. The traditional understanding of difficult separations is that the number of stages needs to be increased at a certain reflux ration and vice versa. In both systems, a tray analysis was completed while maintaining the reflux ratio. Tables 3, 4, 5 list the purities for ethylene and ethane for the number of trays ranging from 5 to 100 in an ordinary distillation tower. Tables 6, 7 and 8 list the purities of ethylene and ethane for the vapor recompression system for the same range of trays. Results show that the purity of ethylene increases with number of trays and increases with decreased pressure. This is because each additional tray acts as an extra equilibrium contactor allowing for more mass transfer to occur. The more "stages" there are, the more mass transfer occurs which results in a purer product.

Table 3. Tray Analysis Ordinary Distillation 2000kPa

	2		3	
Trays	**Ethylene Purity**	Ethane Purity	**Ethylene Purity**	Ethane Purity
100	**0.9981**	0.0019	**0.0028**	0.9972
95	**0.9977**	0.0023	**0.0034**	0.9966
90	**0.9972**	0.0028	**0.0042**	0.9958
85	**0.9963**	0.0037	**0.0055**	0.9945
80	**0.9956**	0.0044	**0.0069**	0.9931
75	**0.9946**	0.0054	**0.0078**	0.9922
70	**0.9935**	0.0065	**0.0100**	0.9900
65	**0.9922**	0.0078	**0.0122**	0.9878
60	**0.9904**	0.0096	**0.0149**	0.9851
55	**0.9881**	0.0119	**0.0185**	0.9815
50	**0.9849**	0.0151	**0.0233**	0.9767
45	**0.9803**	0.0197	**0.0302**	0.9698
40	**0.9734**	0.0266	**0.0405**	0.9595
35	**0.9628**	0.0372	**0.0560**	0.9440
30	**0.9508**	0.0492	**0.0744**	0.9256
25	**0.9343**	0.0657	**0.0988**	0.9012
20	**0.9116**	0.0884	**0.1324**	0.8676
15	**0.8793**	0.1207	**0.1804**	0.8196
10	**0.8317**	0.1683	**0.2524**	0.7476
5	**0.7667**	0.2333	**0.3500**	0.6500

Table 4. Tray Analysis Ordinary Distillation 1000kPa

	2		3	
Trays	**Ethylene Purity**	Ethane Purity	**Ethylene Purity**	Ethane Purity
100	**0.9994**	0.0006	**0.0009**	0.9991
95	**0.9992**	0.0008	**0.0011**	0.9989
90	**0.9990**	0.0010	**0.0015**	0.9985
85	**0.9987**	0.0013	**0.0019**	0.9981
80	**0.9984**	0.0016	**0.0024**	0.9976
75	**0.9980**	0.0020	**0.0031**	0.9969
70	**0.9974**	0.0026	**0.0039**	0.9961
65	**0.9967**	0.0033	**0.0049**	0.9951
60	**0.9959**	0.0041	**0.0062**	0.9938
55	**0.9947**	0.0053	**0.0079**	0.9921
50	**0.9931**	0.0069	**0.0102**	0.9898
45	**0.9906**	0.0094	**0.0141**	0.9859
40	**0.9862**	0.0138	**0.0206**	0.9794
35	**0.9802**	0.0198	**0.0298**	0.9702
30	**0.9715**	0.0285	**0.0429**	0.9571
25	**0.9588**	0.0412	**0.0619**	0.9381
20	**0.9401**	0.0599	**0.0899**	0.9101
15	**0.9116**	0.0884	**0.1326**	0.8674
10	**0.8662**	0.1338	**0.2008**	0.7992
5	**0.8030**	0.1970	**0.2955**	0.7045

Table 5. Tray Analysis Ordinary Distillation 200kPa

	2		3	
Trays	**Ethylene Purity**	Ethane Purity	**Ethylene Purity**	Ethane Purity
100	**0.9969**	0.0031	**0.0047**	0.9953
95	**0.9968**	0.0032	**0.0048**	0.9952
90	**0.9967**	0.0033	**0.0050**	0.995
85	**0.9965**	0.0035	**0.0052**	0.9948
80	**0.9963**	0.0037	**0.0055**	0.9945
75	**0.9961**	0.0039	**0.0059**	0.9941
70	**0.9957**	0.0043	**0.0064**	0.9936
65	**0.9954**	0.0046	**0.0070**	0.993
60	**0.9949**	0.0051	**0.0077**	0.9923
55	**0.9942**	0.0058	**0.0087**	0.9913
50	**0.9934**	0.0066	**0.0099**	0.9901
45	**0.9925**	0.0075	**0.0113**	0.9887
40	**0.9910**	0.0090	**0.0136**	0.9864
35	**0.9883**	0.0117	**0.0176**	0.9824
30	**0.9840**	0.0160	**0.0240**	0.976
25	**0.9771**	0.0229	**0.0349**	0.9651
20	**0.9650**	0.0350	**0.0526**	0.9474
15	**0.9437**	0.0563	**0.0844**	0.9156
10	**0.9047**	0.0953	**0.1430**	0.857
5	**0.8507**	0.1493	**0.2239**	0.7761

Table 6. Tray Analysis Vapor Recompression Distillation 2000kPa

Trays	**Ethylene Purity**	Ethane Purity
100	**1.0000**	0.0000
95	**1.0000**	0.0000
90	**1.0000**	0.0000
85	**1.0000**	0.0000
80	**1.0000**	0.0000
75	**1.0000**	0.0000
70	**1.0000**	0.0000
65	**1.0000**	0.0000
60	**1.0000**	0.0000
55	**0.9999**	0.0001
50	**0.9999**	0.0001
45	**0.9998**	0.0002
40	**0.9996**	0.0004
35	**0.9993**	0.0007
30	**0.9917**	0.0083
25	**0.9839**	0.0161
20	**0.9687**	0.0313
15	**0.9441**	0.0559
10	**0.8905**	0.1095
5	**0.7952**	0.2048

Table 7. Tray Analysis Vapor Recompression Distillation 1000kPa

Trays	**Ethylene Purity**	Ethane Purity
100	**1.0000**	0.0000
95	**1.0000**	0.0000
90	**1.0000**	0.0000
85	**1.0000**	0.0000
80	**1.0000**	0.0000
75	**1.0000**	0.0000
70	**1.0000**	0.0000
65	**1.0000**	0.0000
60	**1.0000**	0.0000
55	**0.9999**	0.0001
50	**0.9999**	0.0001
45	**0.9998**	0.0002
40	**0.9997**	0.0003
35	**0.9995**	0.0005
30	**0.9991**	0.0009
25	**0.9979**	0.0021
20	**0.9613**	0.0387
15	**0.9384**	0.0616
10	**0.8968**	0.1032
5	**0.7846**	0.2154

Table 8. Tray Analysis Vapor Recompression Distillation 200kPa

Trays	**Ethylene Purity**	Ethane Purity
100	**0.0127**	0.9873
95	**0.0127**	0.9873
90	**0.0128**	0.9872
85	**0.0128**	0.9872
80	**0.0130**	0.9870
75	**0.0131**	0.9869
70	**0.0134**	0.9866
65	**0.0138**	0.9862
60	**0.0143**	0.9857
55	**0.0150**	0.9850
50	**0.0164**	0.9836
45	**0.0177**	0.9823
40	**0.0200**	0.9800
35	**0.0243**	0.9757
30	**0.0323**	0.9677
25	**0.0448**	0.9552
20	**0.0692**	0.9308
15	**0.1114**	0.8886
10	**0.1569**	0.8431
5	**0.2846**	0.7154

5 Conclusion

An analysis was carried out on HYSYS process development software with a vapor recompression system and an ordinary distillation system set at pressures of 200, 1000 and 2000 kPa. Results confirmed that Ethylene purity increased with reflux ratio for all the pressures studied although the separation became more difficult as the pressure increased. Analysis also confirmed that the number of trays also had a significant impact on the purity of ethylene. In addition the results demonstrated that purity of ethylene increased with number of trays and decreased pressure. When comparing the vapor recompression system (VRC) with the ordinary distillation system (OD) the analysis proved that the VRC system was much more efficient and had a much less duty compared to the OD system. Further trials should be conducted with other pressures to better demonstrate data approaching 99.9% purity. Flow rates of 100kPa, 500kPa, 1500kPa are possible choices for further analysis.

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APPENDIX

VISIO sketches of the Ordinary Distillation system (top) and the Vapor Recompression System (bottom).