

Felles-lab ST2:
Distillation, Oldershow perforated plate
Workplan

Åge Johansen

agej@stud.ntnu.no

Yngve Mannsåker Hereide

yngvemh@stud.ntnu.no

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1 Introduction

The purpose of this experiment has been to acquire knowledge of the different principles of distillation by examining an Oldershaw perforated plate distillation column. Column efficiency, theoretical trays and vapour velocity at steady states for different reboiler power outputs have been determined, and the properties of the weeping and the flooding point have also been explored.

2 Theory

The theory in this experiment is gathered from [1] and [2].

2.1 Basic principles of distillation

Distillation is a separation method for separating two different liquids based on the differences in boiling temperature. Distillation takes place in a column which is created to give a maximum vapour/liquid interaction in order to reach the vapour/liquid equilibrium (VLE). This is done by using trays which gives a large liquid front. The trays are mounted on top of each other which can be seen in figure 1 which is gathered from Geankoplis [2]. In general, the more trays, the better separation is possible to achieve. The distillation column is heat driven by a reboiler in the bottom of the column which evaporates the liquid. As the vapour makes progress upwards in the column it is contacted with liquid going downward the VLE establishes and the component with the lowest boiling point condensates. At the top of the column is a condenser which cools down the vapour so it condensates. From this condensate the flow can be directed into product (distillate) or back into the column (reflux). If all condensate is directed back to the column, one says that the column is operated in total reflux mode.

2.2 Weeping point

A weeping point is a condition in the distillation column which occur when the vapour velocity is too low. The vapour pressure is not sufficient to hold up the liquid in a tray. Instead the liquid will flow through the perforated holes in the tray and will "weep" out underneath. The vapour loses contact with the liquid, and this causes both the pressure and the efficiency to drop.

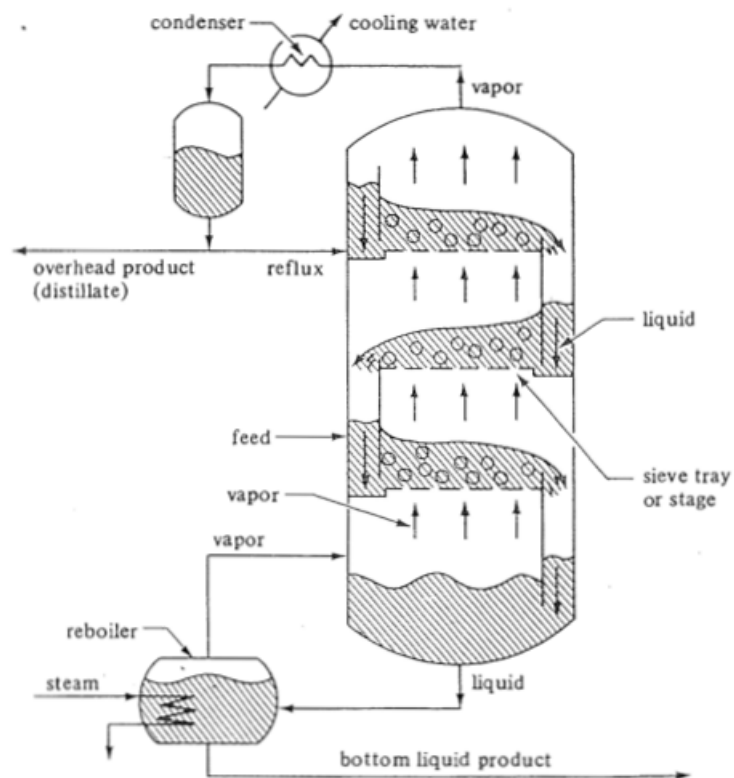


Figure 1: The figure is showing a fractionated distillation column containing sieve trays. The figure is gathered from chapter 11.4A in Geankoplis [2]

2.3 Flooding point

The capacity of a counter current (liquid flows downwards and vapour flows upwards) separation is called a flooding point. At the flooding point liquid will accumulate in the column as a result of the high vapour velocity which causes the pressure from the vapour to hold back the liquid from the down-comers. This increases the drop in pressure, resulting in a lower column efficiency.

2.4 Column efficiency

The efficiency of a distillation column is given by the ratio of the total number of ideal equilibrium stages and the total number of actual trays in the column. A high efficiency means that for each stage, the upcoming vapour is in equilibrium with the liquid which floods downwards. The equation for this is given in (2.1),

$$\eta = \frac{N_t - 1}{N_a} \quad (2.1)$$

where the -1 indicates that the reboiler is regarded as one tray.

2.5 Reflux

Reflux is the portion of the vapour that condenses and is returned to the distillation column. The reflux ratio is given by (2.2),

$$R_R = L_n/D \quad (2.2)$$

where R_R is the reflux ratio, L_n is the condensed liquid flow back into the column and D is the distillate flow out of the column. If the column is operated in total reflux mode, this means that all condensate flows back into the column so that $R_R \rightarrow \infty$. This has an effect of the calculation of the operating lines. This means that the slope of the operation lines given in equation (2.3) and (2.4) becomes $\frac{\infty}{\infty} = 1$ so that the operating line is in a 45° angle.

2.6 McCabe-Thiele method

The McCabe Thiele method is a graphical method for calculating the total number of theoretical trays in a given binary separation process. The method uses an assumption of constant molar overflow, which means that the vapour flow rate and molar liquid flow rate both are constant for all stages in a section of the column. Because of this the operating line is considered to be a

straight line. Using mass balances and vapour-liquid equilibrium data (VLE) (section A.3-23 in Geankoplis [2]) for both components a McCabe-Thiele diagram (Figure 2) can be generated and the number of theoretical stages can be determined graphically. In a McCabe-Thiele diagram, the x-axis shows the mole fraction of the light component (the component with the lowest boiling temperature) in liquid phase, the y-axis shows the mole fraction of the light component in the gas phase. The VLE-data gives an equilibrium line which should lie above the operating lines which is generated from mass-balances and reflux ratios.

There are two operating lines. One for the enriching section (section of the column where the mole fraction of light component is higher than the feed) and one for the stripping section (section of the column where mole fraction of light component is lower than the feed). The enriching operating line is solved in equation (2.3),

$$y_{n+1} = \frac{R_R}{R_R + 1}x_n + \frac{x_D}{R_R + 1} \quad (2.3)$$

where R_R is the reflux ratio, x_n is the mole fraction of light component in liquid phase at tray n , x_D is the mole fraction of light component in the distillate. The stripping operating line is solved in equation (2.4),

$$y_{m+1} = \frac{L_m}{V_{m+1}}x_m - \frac{Wx_W}{V_{m+1}} \quad (2.4)$$

where L_m is the liquid flow from tray m , V_{m+1} is vapour flow from tray $m+1$, x_m is the mole fraction of light component in the liquid phase at tray m , W is the flow out of the column at the bottom and x_W is the mole fraction of light component in the out flow.

The feed condition determine the relationship between the the vapour in the stripping section V_m and vapour in the enriching section V_n , as well as the liquid phases, L_m and L_n . If the feed is dual phase, the vapour will add to V_m to give V_n . This condition is defined by q (equation 11.4-12 in Geankoplis [2])

$$q = \frac{\text{heat needed to vaporize 1 mol of feed at entring condiction}}{\text{molar latent heat of vaporization of feed}}$$

In the McCabe-Thiele diagram, q is used to create a q -line with slope $\frac{q}{q-1}$, going through the point (x_f, y_f) , where x_f is the molar fraction of light component in liquid phase in feed. q gives properties for the q -line given in table

Table 1: The table shows the properties of the q -line for different values of q

q value	q -line	Properties of feed
$q = 1$	vertical	Feed enters at boiling point
$q = 0$	horizontal	Feed enters at dew point
$q > 1$	Positive slope	Feed is cold liquid
$q < 0$	Negative slope	Feed is superheated vapour

Figure 2: The figure shows the McCabe-Thiele diagram for ethanol/water mixture, plotted for ethanol.

1. The number of theoretical stages is then determined using the following steps:
 1. Start at top tray where $x = x_D$.
 2. Draw a horizontal line until you hit the equilibrium line. This point is tray 1.
 3. Draw a vertical line until you hit the operating line.
 4. Count and repeat step 2 until you hit $x = x_B$.

By using the MATLAB-scripts in Appendix B the following McCabe Thiele diagram was generated.

2.7 Gas chromatography (GC)

Gas chromatography was used in this experiment to calculate the composition in the samples gathered from the apparatus. Gas chromatography is often used for separation of small quantities. The sample in question is heated and injected into a glass column where inert gas transports the mobile phase (the test sample) forward. Sample components are separated based on their boiling points and relative affinity for the stationary phase. The higher a component's affinity for the stationary phase, the slower it comes off the column. The components are then detected and represented as peaks on a chromatogram.[?]

3 Experimental

The following section describes the set up and procedure of the experiment.

3.1 Startup

The computer and the cooling water was turned on and the bottom and distillate taps were closed, and 5.8 L of a solution containing 11% ethanol and 89% water was poured into the boiler. The column was then started with total reflux, meaning that all the distillate was led back into the top of the column by a pump. In order to prevent the thermostat from interfering with the power supply the target temperature was set to 105 °C, which is a higher temperature than the boiling temperature of the solution. The boiler was set to have a power output of 40% of its maximum 4 kW, and the timer was started when the vapour stream started to condensate inside the cooler.

3.2 Time required to reach steady state

The first experimental task was to measure how long time it would take for the column to reach steady state. Therefore, starting at $t = t_0$, 12 distillate samples were collected with intervals of approximately 5 min in order to examine the composition of the distillate over time. (The data collected in this procedure are plotted in the diagram shown in Figure 3.)

3.3 Efficiency vs. vapour velocity

After the first thirteen samples had been collected, the boiler's power output was adjusted to 50% and let to stand for 30 min to ensure that steady state had been reached. Samples were then taken from both the distillate and the batch in the reboiler, and the reflux ratio was logged so that the vapour speed could be calculated. This procedure was then repeated with the power output at 60%, 70%, 80% and 90%.

3.4 Flooding and weeping point

To find the weeping point of the column, the reboiler's power output was lowered until liquid started seeping through the perforations in the plates. This occurred when the power output was set to somewhere between 5% and 10%. To find the flooding point, the power output was set to 100% (i.e. 4 kW), but this was still not sufficient to flood the column. The supervisor estimated that it would probably be necessary with a power source of 8 kW in order to properly flood the column.

3.5 Gas chromatography (GC)

500 μL of each sample taken during the experimental procedure was mixed with 250 μL isopropanol and analysed by gas chromatography to establish their composition.

3.6 Ethanol-water mixture

In this experiment a solution with 11% ethanol was needed to distillate. By using section C with $x_{et} = 0.11, \rho_{et} = 0.785 \text{ g cm}^{-3}, \rho_w = 1000 \text{ g cm}^{-3}, M_w = 18.02 \text{ g mol}^{-1}, V_{tot} = 5.8 \text{ L}$. The volume of ethanol needed is $V_{et} = 1.655 \text{ L}$. Only 96% ethanol is used so $V_{et,96\%} = \frac{1.655}{0.96} = 1.724 \text{ L}$ is needed.

4 Results

All samples were analysed using gas chromatography, however something went terribly wrong after the 12th sample. This means that all samples after the 55 min sample are useless. In order to complete the exercise, a set of constructed top and bottom samples was constructed, as shown in Figure 5. The actual results are found in table 4. Further discussion regarding the actual results are given in section 5.

4.1 Time required to reach steady state

Figure 3 shows the mole fractions of ethanol in the distillate plotted against time, in seconds, the values are taken from table 4. Some of the samples shows a mole fraction higher than 1 (which is impossible). From figure 3 it seems that steady state is reached after about 12 minutes, but be aware that the samples has a high uncertainty as two samples got an higher molefraction than 1.

4.2 McCabe-Thiele diagrams

The following diagrams are generated from made up top and bottom fractions given in table 5

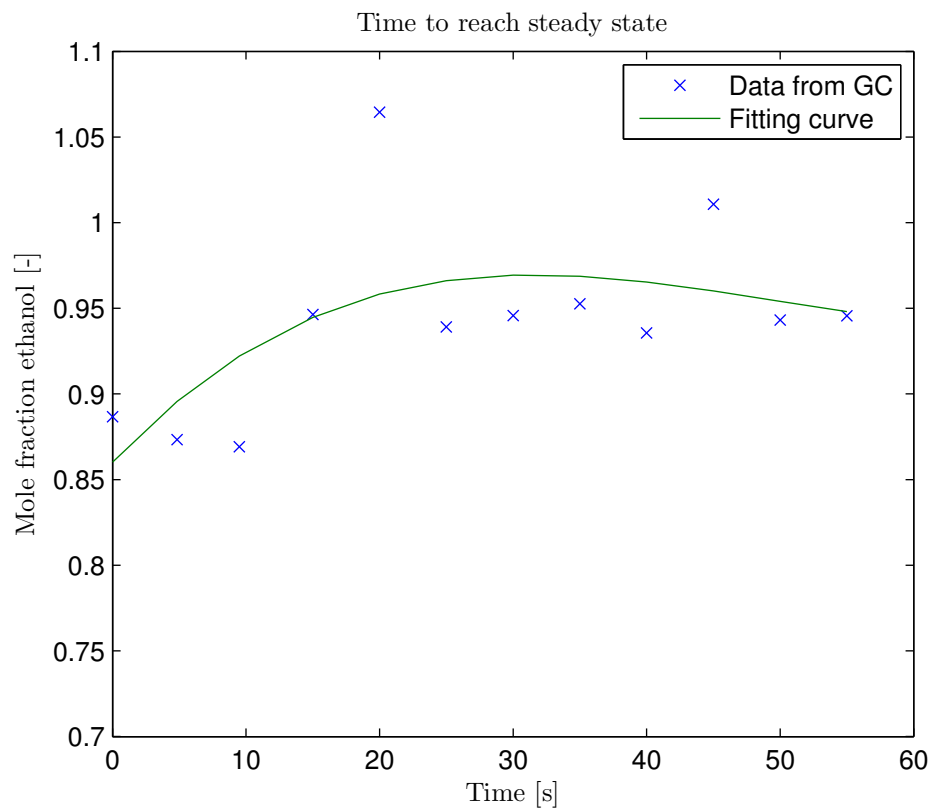


Figure 3: Plot of the mole fractions of the sample tests after a given time. The fitted curve was found using MATLAB's polyfit tool with a 3rd degree polynomial.

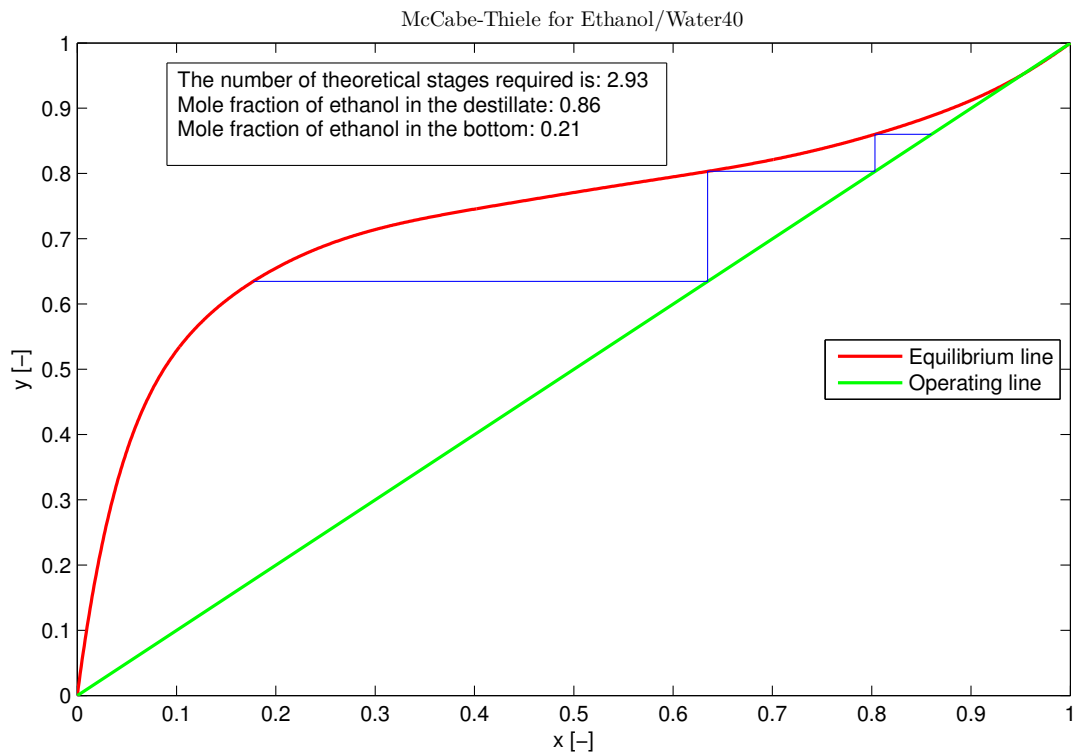


Figure 4: The figure shows the McCabe-Thiele diagram for column with a power output of 40%. x is the mole fraction of ethanol in liquid phase and y is the mole fraction of ethanol in the vapour phase. The plot calculating the number of theoretical steps is made from the MATLAB-script in B.1

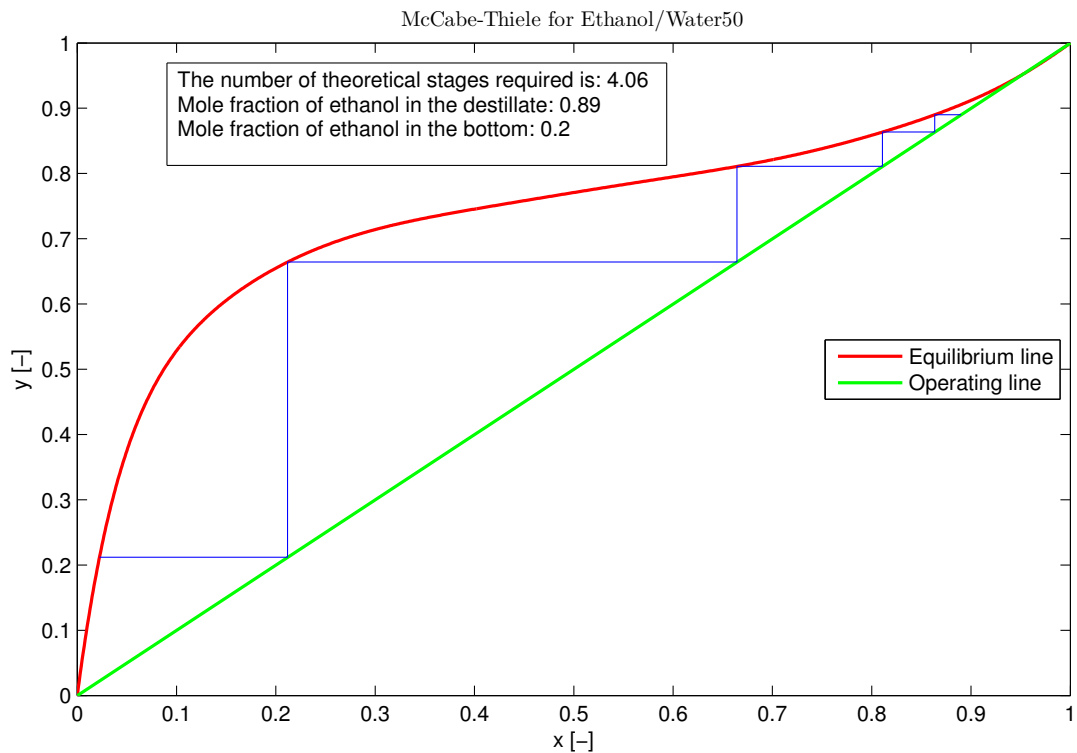


Figure 5: The figure shows the McCabe-Thiele diagram for column with a power output of 50%. x is the mole fraction of ethanol in liquid phase and y is the mole fraction of ethanol in the vapour phase. The plot calculating the number of theoretical steps is made from the MATLAB-script in B.1

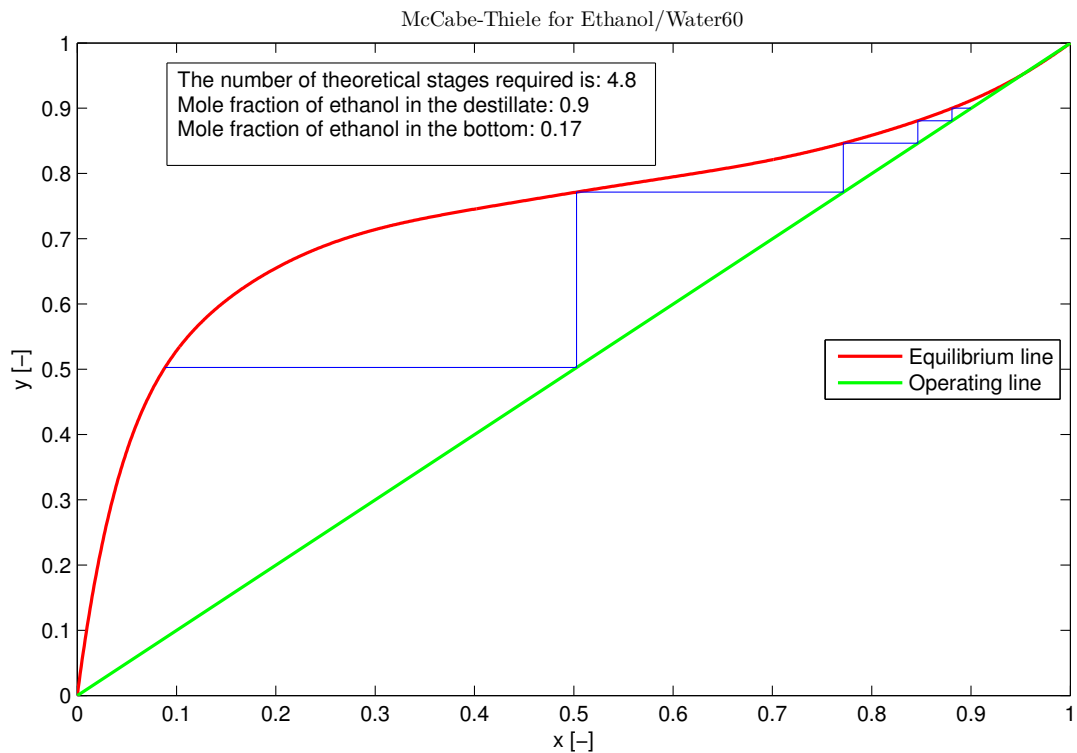


Figure 6: The figure shows the McCabe-Thiele diagram for column with a power output of 60%. x is the mole fraction of ethanol in liquid phase and y is the mole fraction of ethanol in the vapour phase. The plot calculating the number of theoretical steps is made from the MATLAB-script in B.1

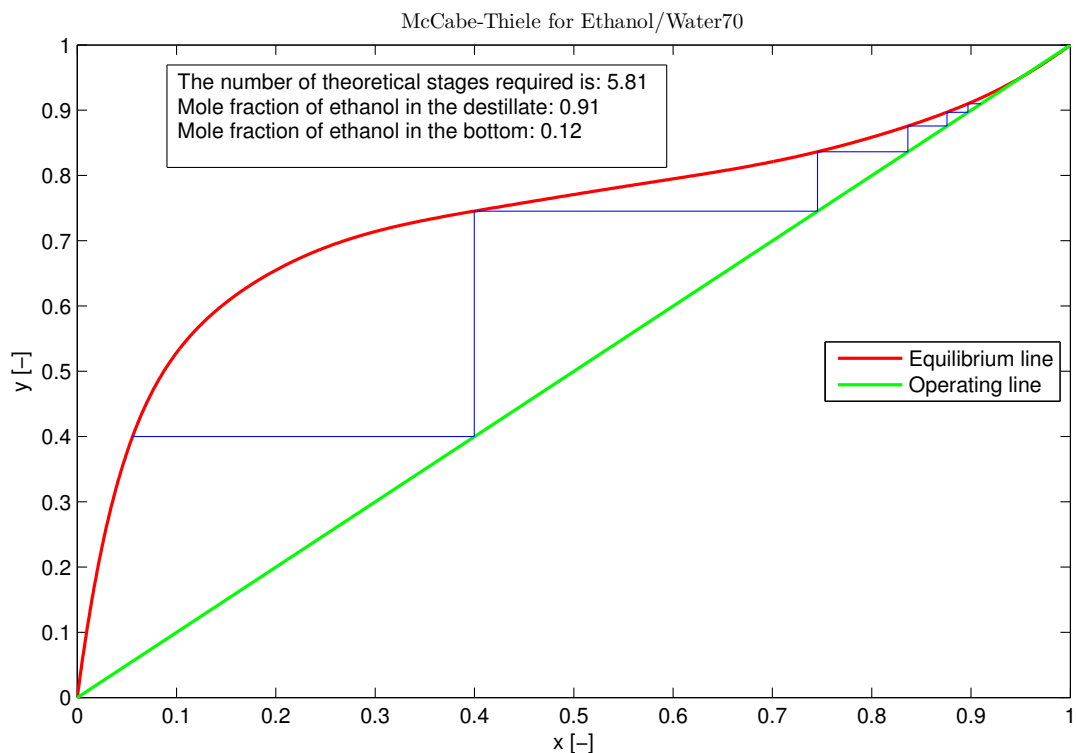


Figure 7: The figure shows the McCabe-Thiele diagram for column with a power output of 70%. x is the mole fraction of ethanol in liquid phase and y is the mole fraction of ethanol in the vapour phase. The plot calculating the number of theoretical steps is made from the MATLAB-script in B.1

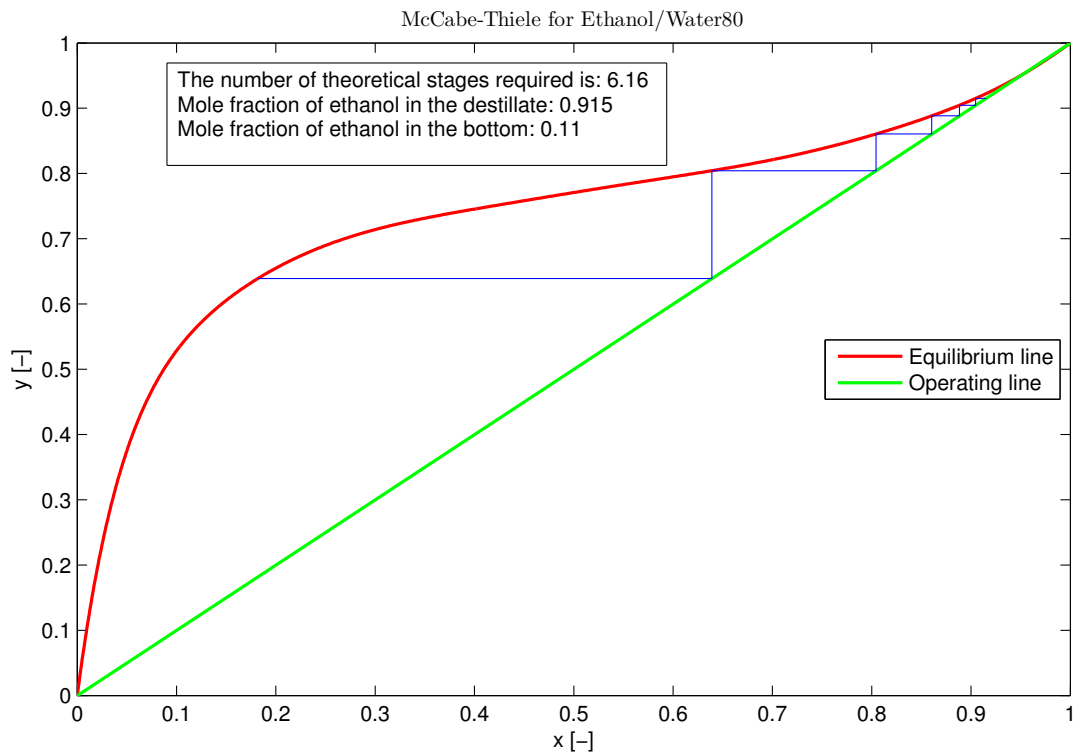


Figure 8: The figure shows the McCabe-Thiele diagram for column with a power output of 80%. x is the mole fraction of ethanol in liquid phase and y is the mole fraction of ethanol in the vapour phase. The plot calculating the number of theoretical steps is made from the MATLAB-script in B.1

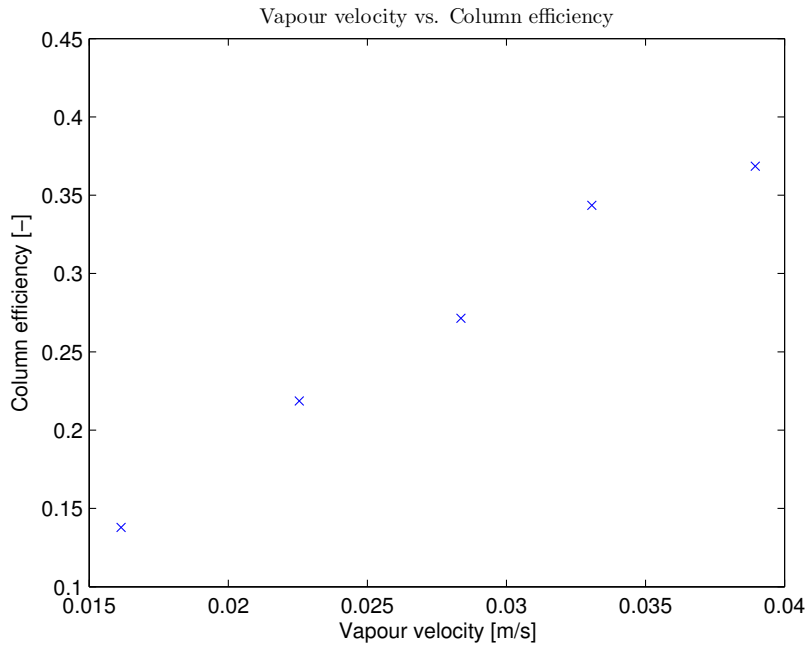


Figure 9: The figure is showing a plot of column efficiency vs. the vapour velocity for the power duties 40, 50, 60, 70 and 80%

4.3 Column efficiency vs. vapour velocity

The column efficiency was calculated from equation (2.1), with $N_a = 14$. The vapour velocity was calculated from (F.7). It was assumed that $y_i = V_i/V_{tot}$ could be calculated directly from the VLE-data using x_d from the sampling. Figure 9 shows the plot of column efficiency vs. the vapour velocity for each power duty.

5 Discussion

The gas chromatography did not work as expected. The first 12 samples gave reasonable results (except from two samples who had a mole fraction above 1). After the 12 first samples something went wrong, as can be seen in Table 4. First, all top samples for the power duty of 50%, 60%, 70% and 80% gave a mole fraction of zero, although the result for the top samples should be around 90%. The test indicates that the ethanol mole fractions of the bottom samples are too high to make any sense. Typically, a bottom sample should contain an ethanol mole fraction of 5 to 15 %_{wt} ethanol, but the GC test show numbers that are far higher than this (although the numbers decrease from 62%_{wt} to 26%_{wt}). All of these figures are much higher than the

starting concentration of 11%_{wt} and therefore make little sense. What might have caused this is difficult to point out, but it is quite certain that the error doesn't lie in the mixing of the distillation solution as the amounts of water and ethanol were checked and double checked before mixing. All the sample tests prepared for GC had propanol added to them in the correct amount (250 µL) and were thoroughly shaken by both members of the experiment group, so it is difficult to see what might have happened. One possibility is that someone not involved in the experiment has moved the prepared samples around in or out of the GC machine carousel causing the top sample zeros. This does however not explain the high concentrations in the bottom samples.

Steady state for the column is reached when the the graph in Figure 3 flattens out. As seen in the figure, the graph looks flat after 15 minutes. However, there is a high uncertainty from the GC, as described in the previous paragraph and as seen in figure, the graph actually turns near the end because of the outliers (points where $x_d > 1$).

The best setting for the column is the peak of the column efficiency. The column efficiency tends to increase with higher vapour velocity, meaning that the best setting for the column is when the power duty is above 80%. Please note that figure 9 was calculated from constructed data, so for the real data there may have been a peak at some point between 40-80%.

6 Conclusion

The time required to reach steady state was estimated to approximated to around 15 min. Even at 4kW (full power) flooding was not observed, so it was concluded that there was impossible to flood the column. The weeping point was observed at approximately 10% power duty (400 W). This means that the minimum power required in order to distillate was above 400 W. The theoretical number of trays required at different power duties was calculated using MATLAB and was found to 2.93, 4.06, 4.8, 5.81 and 6.1 for power duties of 40,50,60,70,80% respectively. Please note that this was calculated for constructed data due to useless results from the GC-analysis. The column efficiency increased with higher vapour velocity (higher power output) and was 0.369 at a power duty of 80%.

References

- [1] Felles lab: Distillation Columns, http://www.nt.ntnu.no/users/preisig/Repository/TKP_4110_Felles_Lab/experiment%20descriptions/DistInstruct.pdf, visited: 1.10.2013
- [2] Geankoplis, Christie John *Transport Processes and Separation Process Principles (includes unit operations)*, 4. ed; Prentice Hall, 2003
- [3] Perry, R.H and Green, D.W, *Perry's Chemical engineers' Handbook*, 8. ed; McGraw-Hill, 2008

A MATLAB

A.1 Steady state plot

```
function p = steadystate(inputfile)
    data = load('steadystate.txt');
    time = data(:,2);
    frac = data(:,1);
    p = polyfit(time,frac,3);
    f = polyval(p,time);
    figname = ['Time to reach steady state'];
    hFig = figure('Name',figname,'Visible','on');
    set(hFig,'NumberTitle','off');
    plot(time,frac,'x',time,f,'-');
    axis([0 60 0.7 1.1])
    legend('Data from GC', 'Fitting curve')
    xlabel('Time [s]','Interpreter','LaTeX');
    ylabel('Mole fraction ethanol [-]','Interpreter','LaTeX');
    title(figname,'Interpreter','LaTeX');
    exportname = ['steadystate'];
    export_fig(exportname, '-pdf', '-transparent')
end
```

A.2 Number of theoretical steps

```
%\begin{minted}[frame=lines]{matlab}
%This script plots the equilibrium line for a binary mixture of ethanol and
```

```
%water, and calculates the number of steps needed to reach a certain
%concentration with total reflux.
%PART 1 - Plotting the equilibrium line and the operating line
xy = load('vle2.txt');
x = xy(:,1);
y = xy(:,2);
%Distillate composition, xd and bottom composition, xb
xd = [0.86 0.89 0.90 0.91 0.915];
xb = [0.21 0.20 0.17 0.12 0.11];
pow = [40 50 60 70 80];
for i=1:length(xd)
    %x is the mole fraction of ethanol in the liquid phase, and y is ...
    %the mole
    %fraction of ethanol in the gas phase.
    %Fit a polynom of tenth degree, p, to fit the data
    p = polyfit(x,y,10);
    %plot p and the operating line y = x

    hFig = figure('Name','McCabe-Thiele','Position',[50 150, 800, 500]);
    eq = plot(0:0.001:1,polyval(p,0:0.001:1));
    set(eq, 'Color','red','LineWidth',1.5)
    op = line([0 1],[0 1]);
    set(op, 'Color','green','Linewidth',1.5)
    axis([0 1 0 1]);
    xlabel('x [-]');
    ylabel('y [-]');
    legend('Equilibrium line', 'Operating line','Location','East');

%Calculating and plotting theoretical stages
% gets input from the function molefraction.m
                                %puts in wanted values

    xs=[];
    ys=[];
% Starts at the top at the operatingline y=x
    xs(1)=xd(i);
    ys(1)=xd(i);
    f =@(x,y)(p(1)*x^10+p(2)*x^9+p(3)*x^8+p(4)*x^7+p(5)*x^6+p(6)*x^5+...
    p(7)*x^4+p(8)*x^3+p(9)*x^2+p(10)*x^1+p(11) - y);%Solve the equation
    j=1; %making a counter
        while xs(j)>xb
            xs(j+1)=fzero(f,0.5,[],ys(j));
```

```
        line([xs(j) xs(j+1)], [ys(j) ys(j)], 'color', 'b');
        ys(j+1)=xs(j+1);
        if xs(j+1)>xb
            line([xs(j+1) xs(j+1)], [ys(j) ys(j+1)], 'color', 'b');
        end
        j=j+1;
    end

%Calculating number of theoretical steps
    N=j-2+(xb(i)-xs(j-1))/(xs(j)-xs(j-1));
    N=round(N*100)/100;
    str={'The number of theoretical stages required is: ' num2str(N)},...
        ['Mole fraction of ethanol in the distillate: ' ...
        num2str(round(xd(i)*1000)/1000)],...
        ['Mole fraction of ethanol in the bottom: ' ...
        num2str(round(xb(i)*1000)/1000)]};
    stbox = annotation('textbox', [0.2 0.8 0.1 0.1], 'String', str);
    figname = ['McCabe-Thiele for Ethanol/Water', num2str(pow(i))];
    title(figname, 'Interpreter', 'LaTeX')
    set(hFig, 'NumberTitle', 'off', 'Visible', 'off');
    exportname = num2str(pow(i));
    export_fig(exportname, '-pdf', '-transparent');
    pow(i)

end

% Create the table of constructed data for the experiment in LaTeX code
fileID =fopen('xdxb.txt', 'w');
fprintf(fileID, '%s \r\n', '\toprule')
fprintf(fileID, '%s & %s & %s %s \r\n ', 'Reboiler power', '$x_d$ [-]' ...
    , '$x_b$ [-]', '\\');
fprintf(fileID, '%s \r\n', '\midrule');
for i=1:length(xb)
    fprintf(fileID, '%-3.f & %5.3f & %5.3f %s \r\n', pow(i), ...
        xd(i), xb(i), '\\');
end
fprintf(fileID, '%s', '\bottomrule')
fclose(fileID);
```

A.3 Calculation and plot of vapour velocity vs. column efficiency

```
function v = effiplot(effi,xd,p)
%Plots the efficiency vs. vapour velocity
reflow = [57.2 82.5 105 124 147]; %ml/min
reflow = reflow*1e-6*(1/60); %m3/s
R = 8.314; %J/Kmol
rhoetoh = 785; % kg/m3
rhowat = 997; %kg/m3
A = 3.8E-3; %m2
T = 363; %K
P = 10e5; %kg/ms2
metoh = 4.607e-2; %kg/mol
mwat = 1.802e-2; %kg/mol
f =@(x)(p(1)*x^10+p(2)*x^9+p(3)*x^8+p(4)*x^7+p(5)*x^6+p(6)*x^5+...
        p(7)*x^4+p(8)*x^3+p(9)*x^2+p(10)*x^1+p(11));
for i=1:length(reflow)
    v(i) = ((R*T)/(A*P))*(reflow(i)*((f(xd(i))*rhoetoh/metoh)+...
        ((1-f(xd(i)))*rhowat/mwat)));
end
hFig = figure('Name','Vapour velocity');
figname = ['Vapour velocity vs. Column efficiency'];
plot(v,effi,'x')
xlabel('Vapour velocity [m/s]')
ylabel('Column efficiency [-]')
title(figname,'Interpreter','LaTeX');
set(hFig,'NumberTitle','off','Visible','off');
export_fig('velocity','-pdf','-transparent');
end
```

B Equations for Ethanol-water mixture

The mole fraction for a given component i is given by equation (C.1),

$$x_i = \frac{n_i}{n_{tot}} \quad (\text{B.1})$$

where n_i stands for the number of mole for component i , and n_{tot} for the total number for mole in the mixture. Number of moles when using pycnometers

is given by equation (C.2),

$$n_i = \frac{V_i \rho_i}{M_i} \quad (\text{B.2})$$

where V_i is the volume of component i , ρ the density and M the molar weight. For the mixture of water and ethanol, the number of moles of ethanol is given by the following equation,

$$n_w = \frac{\rho_w (V_{tot} - V_{et})}{M_w} \quad (\text{B.3})$$

where index $_{et}$ is ethanol and $_w$ is water. The mole fraction of ethanol can be found by combining (C.1), (C.2) and (C.3).

$$x_{et} = \frac{\frac{V_{et} \rho_{et}}{M_{et}}}{\frac{V_{et} \rho_{et}}{M_{et}} + \frac{\rho_w (V_{tot} - V_{et})}{M_w}} \quad (\text{B.4})$$

C Results from GC

Table 2: The table is showing the results from the Gas Chromatography. The 5th column explains the sample content. So that 50 means sample taken after 50 minutes.

Sample name	Sampling time	Carousel #	x_{EtOH}	Sample content
B16_1	13:29	81	0,88675493	0
B16_2	13:34	82	0,8733395338	4,8333333333
B16_3	13:40	83	0,8692047	9,5
B16_4	13:45	84	0,9464284182	15
B16_5	13:50	85	1,0645126104	20
B16_6	13:56	86	0,9390891194	25
B16_7	14:01	87	0,9457674026	30
B16_8	14:11	88	0,9525999427	35
B16_9	14:22	89	0,9356185198	40
B16_10	14:27	90	1,0107297897	45
B16_11	16:46	91	0,9431585073	50
B16_12	16:51	92	0,9456739426	55
B16_13	16:57	93	0,664142549	40btm
B16_14	17:07	94	0	50top
B16_15	17:13	95	0,619551897	50btm
B16_16	17:18	96	0	60top
B16_17	17:23	97	0,5991532803	60btm
B16_18	17:29	98	0	70top
B16_19	17:34	99	0,3690922856	70btm
B16_20	17:41	100	0	80top
B16_21	17:46	101	0,2554974258	80btm

D Constructed data

The data in table 5 was constructed in order to complete the rapport as there was something terribly wrong with the results from the gas chromatography.

Table 6 shows how the efficiency correlates to the number of theoretical steps for the constructed data.

Table 3: The table is showing the constructed output from the top and bottom. These data are used for all calculations regarding comparing different column settings.

Reboiler power	x_d [-]	x_b [-]
40	0.860	0.210
50	0.890	0.200
60	0.900	0.170
70	0.910	0.120
80	0.915	0.110

Table 4: The table is showing the number of theoretical steps and the column efficiency for different power duties.

Reboiler power	Theoretical steps, N	Efficiency η
40	2.930	0.138
50	4.060	0.219
60	4.800	0.271
70	5.810	0.344
80	6.160	0.369

E Vapour velocity

The mean vapour velocity, v , is given as the volume of gas flowing through the column, \dot{V} , divided by the column's cross section area, A , as shown in (F.1):

$$v = \frac{\dot{V}}{A} \quad (\text{E.1})$$

Assuming ideal gas it is possible to calculate the volume flow of each component, \dot{V}_i , through the molar flow of each component, \dot{n}_i :

$$\dot{V}_i = \frac{RT\dot{n}_i}{p} \quad (\text{E.2})$$

where T is the temperature of the gas and R is the gas constant.

The molar flow of each component, \dot{n}_i , is found by dividing the mass flow of each component, \dot{m}_i , by the molar mass, M_i :

$$\dot{n}_i = \frac{\dot{m}_i}{M_i} \quad (\text{E.3})$$

The mass flow can be calculated by (F.4)

$$\dot{m}_i = \dot{V} \frac{V_i}{V_{tot}} \rho_i \quad (\text{E.4})$$

where \dot{V} is the total volume flow through the reflux column, V_i the volume flow of component i , V_{tot} the **FIND WHICH TOTAL VOLUME THIS IS!**, and ρ_i the density of component i . Combining (F.1), (F.2), (F.3) and (F.4), a more usable expression for v is obtained:

$$v = \frac{RT}{Ap} \frac{\dot{V} \rho_i}{M_i} \frac{V_i}{V_{tot}} \quad (\text{E.5})$$

Using the the relation in (F.6)

$$\dot{n} = n_{EtOH} + n_{H_2O} \quad (\text{E.6})$$

a final expression of v is achieved:

$$v = \frac{RT}{Ap} \left(\frac{\dot{V} \rho_{EtOH}}{M_{EtOH}} \frac{V_{EtOH}}{V_{tot}} + \frac{\dot{V} \rho_{H_2O}}{M_{H_2O}} \frac{V_{H_2O}}{V_{H_2O}} \right) \quad (\text{E.7})$$