JOINT PROJECT OF CHEMICAL ENGINEERING - APPLIED MECHANICS - A WAY TO IMPROVE THE EDUCATION LEVEL OF CHEMICAL ENGINEERING STUDENTS

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ABSTRACT

A methodology for calculation of distillation column for binary system separation completed with constructive calculations of flanges, support and seating (basement) has been proposed as a mutual project of the departments of Chemical Engineering and Applied Mechanics for chemical engineering students. As a result of such interdisciplinary cooperation an enhancement of level of knowledge of the students could be expected, consisted in closing the cycle from chemical engineering project calculations to mechanical calculations and preparing the complete engineering documentation for the equipment.

Keywords: methodology of chemical engineering and applied mechanics education, distillation, constructive column support calculations.

INTRODUCTION

It is well established that the education of chemical and biochemical engineering students must include different knowledge. The project in “Unit Operations” could be a useful example. Usually in the course in “Unit Operations” one of the following projects is included:
- Calculation of distillation equipment: column and 5 heat exchangers;
- Triple effect vacuum evaporation;
- Mechanical purification of gases from dust.

Usually the project calculations are finished after the dimensions of apparatuses are found with standardising and plotting the flow-sheet schema and one of the basic apparatuses. No constructive calculations concerning the weight and the mechanical characteristics of the supporting details are previewed.

On the other hand during the course of Mechanics only standard calculations of simple details are done without any connection with other courses and projects. The courses of “Technical Design” and “Applied Mechanics” are constructed so to provide knowledge in drawing of simple machine elements as screws, bearings, etc., using the current standards in their choice, as well as the basic strength calculations.

That was the reason to propose a possibility for joint project in “Unit Operations” and “Applied Mechanics”. The co-operation of both subjects could provide a good possibility for students to make the usual design calculations of one of the projects in “Chemical
Engineering” together with applying of their knowledge in Mechanics to design the supporting details of chemical equipment, to choose the proper material with respect to its chemical resistance, etc.

On the example of students’ project on distillation equipment we shall show the necessity of mechanical and constructive calculations.

SOLUTION OF DISTILLATION PROBLEMS

The solution proposed is based upon the well-known McCabe Thiele method for binary separations [1-3]. Following assumptions are made:
- constant molar flowrate of both phases;
- on each stage equilibrium is attained;
- the column consists of both stripping and enriching sections;
- the feed enters between these sections;
- the column is being condensed and part of it is withdrawn as a product (distillate), another part is returned in the column as reflux.

PROCEDURE

The following data must be available:
- feed flowrate and composition;
- desired product and residue’s concentrations;
- vapour-liquid equilibrium data at the given operating pressure;
- thermo-physical properties of the components.

- The equilibrium data could be found in the literature [4] or calculated by one of the various methods available [5-8]. The equilibrium data first must be plotted as a graph of the molar fraction of more volatile component in the vapour phase (on the ordinate) versus the molar fraction of more volatile component in the liquid phase (on the abscissa).
- Then the material balance of the column is carried out, as follows:

\[ G_f = G_p + G_w \]  

\[ G_f x_f = G_p x_p + G_w x_w \]  

\[ G_y = G_R + G_p \]

\[ R = \frac{G_R}{G_p} \rightarrow G_y = G_p (R + 1) \]  

- Here \( G_f, x_f \) are the feed flowrate, kmol s\(^{-1}\) and composition; \( G_p, x_p \) - the distillate flowrate, kmol/s and composition and \( G_w, x_w \) - the residue flowrate, kmol s\(^{-1}\) and composition; \( G_y \) is the vapour flowrate, kmol s\(^{-1}\); \( G_R \) is the reflux flowrate, kmol s\(^{-1}\); \( R \) is the reflux ratio.

- Minimal reflux ratio determination (the case when both operating lines are crossed on the equilibrium line):

\[ R_{min} = \frac{x_p - y^*_{f}}{y^*_{f} - x_f} \]

where \( y^*_{f} \) is the concentration of the more volatile component in the vapour in equilibrium with feed flow.

- Optimal reflux ratio determination - by graphical optimisation procedure between optimal column volume and evaporator charge.

- Then a graphical procedure is carried out. It involves the construction of both operating lines the equations for which are as follows:

- Equation of the upper operating line (enriching line):

\[ y = \frac{R}{R+1} x + \frac{x_p}{R+1} \]  

- Equation of the lower operating line (stripping line):

\[ y = \frac{R + f}{R+1} x + \frac{1 - f}{R+1} x_w \]  

Here \( f \) is the feed ratio: \( f = \frac{G_f}{G_p} \).

In both lines' equations the optimal reflux ratio found is used, so the cross point between them is the feed point.

- Determination of number of plates required at optimal reflux ratio - usually a graphical method is used.

- For the case of packed bed columns - choice of package.

- Determination of vapour velocity in the column

** For the packed bed columns first the engagement velocity must be found. The operating velocity is about 20-30% less than the engagement velocity.
**For the case of plate columns the optimal vapour velocity is calculated in dependence with the plate construction.

Calculation and standardising of column diameter - by use of the mass flow-rate equation and the mean density of the vapour in the column:

\[ V_p = \frac{G_p (R+1)T_m V_0}{M_p T_0}, \text{ m}^3 \text{s}^{-1}; \]

\[ T_m = \frac{T_1 + T_2}{2}; V_0 = 22.414 \text{ m}^3 \text{kmol}^{-1} \]  \hspace{1cm} (6)

\[ M_p = x_p M_{mol} + (1-x_p)M_{nc} \text{ kgmol}^{-1} \]

After that the optimal vapours' velocity in the column is to be found, using the equation:

\[ w = \sqrt{\frac{\rho_{iq} - \rho_v}{\rho_v}} \]  \hspace{1cm} (7)

Here \( \rho_{iq} \) and \( \rho_v \) are the densities of the liquid and the vapour. It is evident, that \( \rho_{iq} >> \rho_v \), so the equation could be simplified to:

\[ w = c \sqrt{\frac{\rho_{iq}}{\rho_v}} \]  \hspace{1cm} (7')

\( c \) is a coefficient, depending on plate construction and the column charge. Its values could be found in the literature [9]. For the case of perforated plates \( c = 0.05 \).

Then the column diameter can be easily found from the flow rate equation:

\[ D = \sqrt{\frac{4V}{\pi w}} \]  \hspace{1cm} (8)

Usually the calculations are made with mean fluids' properties for the enriching and the stripping part of the column, so, as a result two diameters are found. Then the column diameter must be standardised. The closest greater standard diameter is to be chosen. Then the correction of the vapour's velocity must be done:

\[ w_r = \frac{w}{w_r} = \frac{4V}{\pi D_{st}^2} \]  \hspace{1cm} (9)

** Column height calculation

** For the case of plate columns the plate effectiveness factor has to be used

\[ \eta_{oy} = \frac{\bar{y}_n - \bar{y}_{n+1}}{y_n* - \bar{y}_{n+1}} \]  \hspace{1cm} (10)

This is the ratio of mean vapours composition change and the composition change when equilibrium is reached. (The plate numbers are increasing from top to bottom of the column). Usually this factor varies among 0.3 and 0.8. For great column diameters \( D > 0.9 \text{ m} \) a correction in the effectiveness factor must be done:

\[ \eta' = \eta (1 + \Delta) \]  \hspace{1cm} (11)

Here the relative volatility also has to be taken into account. In Fig.3 the graphical presentation of this relationship is given [9].

The real plates number in the column is:

\[ n_r = \frac{n_e}{\eta'} \]

which could be used for both column parts separately to find the total column height.

So, for the column height the following relation could be used:

\[ H = (n-1)h + h_1 + h_2 + h_3 \]  \hspace{1cm} (12)

Here \( h \) is a standard distance between the plates [10]; \( h_1 \) is the distance between the upper plate and the cover of the column (about 0.6-0.8 m); \( h_2 \) is the distance between the feed plate and the first plate of the stripping part - about 0.5 m; \( h_3 \) is the distance between the lowest plate and the bottom of the column - about 0.4-0.6 m; \( H \) is the total column height.

** For the case of packed bed columns the packing height is found as a product of NTU and HTU.

- Calculation and standardising of pipes' diameters;
- Heat balance of the column;
- Calculation of heat exchangers.

Usually the calculations in “Unit Operations” project are finishing here, followed by drawings of the flow-sheet of the installation and the distillation column.

The authors propose to continue with the mechanical engineering part, including:

- Calculations and dimensioning of the details subjected to mechanical tension or charge;
- Standardising of calculated details;
• Preparing of work documentation, consisting of specification, general schema, drawings of all the details;
• Choice of the material, suitable for the operating conditions;
• Calculations of the mass of the apparatuses and the supporting details.

As an example a calculation of distillation column will be presented [11].

**WORKING EXAMPLE**

A continuous distillation column for separation of binary mixture benzene-toluene has to be calculated, using the following data:

- Feed flow rate \( G_f = 5 \, \text{kg s}^{-1} \);
- mass fraction of more volatile component (benzene) in:
  - feed composition: \( x_f = 35 \, \% \) mass;
  - product \( x_p = 98 \, \% \) mass;
  - residue \( x_r = 1.7 \, \% \) mass.

**Solution**

1) As a result of the material balance - eq.(1), the product and the residue’s flow rates are found, as follows:

\[
G_w = \frac{G_f (x_f - x_p)}{x_p - x_w} = \frac{5(0.98 - 0.35)}{0.98 - 0.017} = 3.27 \, \text{kg s}^{-1}
\]

\[
G_p = G_f - G_w = 5 - 3.27 = 1.73 \, \text{kg s}^{-1}
\]

2) For the minimal reflux ratio using the eq.(3) the following value was found:

\[
R_{\text{min}} = \frac{0.983 - 0.61}{0.61 - 0.388} = 1.68
\]

To obtain this value the less volatile component concentrations have to be transformed in molar fraction. The equilibrium value of benzene in vapour phase may be found in the literature for equilibrium data [4]. They are presented graphically in Fig.1.

3) To calculate the optimal reflux ratio the reflux exceed values are supposed, by graphical construction, the number of the theoretical plates is calculated, then the Table1 can be constructed.

Here the product \( R(N+1) \) is proportional to the column volume. On the other side the reflux ratio is proportional to the necessary heat income to the column.

**Fig. 1. Equilibrium data for the bynary system benzene-toluene.**

**Table 1. Calculation of optimal reflux ratio.**

| \( \beta \) | 1.07 | 1.36 | 1.74 | 2.33 | 3.30 | 5.26 |
| \( R \)   | 1.80 | 2.28 | 2.93 | 3.92 | 5.55 | 8.83 |
| \( N \)   | 23.0 | 17.0 | 14.50| 12.50| 11.50| 10.00|
| \( R(N+1) \) | 64.4 | 55.8 | 57.00| 61.50| 75.30| 98.30|

So, to obtain the optimal reflux ratio we are looking for minimum in the relationship \( R(N+1) \) versus \( R \) (Fig.2).

It is evident that the minimal column volume corresponds to the reflux ratio of \( R_{\text{opt}} = 2.1 \). So all following calculations will be done with this value of \( R \).

Now the vapour flow rate and the column diameter are to be calculated. The great variety of plate contact equipment commits difficulties in their choice. It depends not only on technological, but also on economical parameters. The column dimensions (height and diameter) are related to liquid and vapour charge,

**Fig. 2. For the optimal reflux ratio calculation.**
as well as to physico-chemical properties of the system. Distillation of liquids without suspended particles at atmospheric pressure and with large enough flow rates usually is carried out in columns with perforated plates. That is the case, that we will demonstrate in the example.

Using eq. (7') for perforated plates, the operating vapours velocity for both column parts is:

\[ w_r = 0.05 \sqrt{\frac{796}{2.73}} = 0.853 \text{ms}^{-1} \]

\[ w_s = 0.05 \sqrt{\frac{796}{2.85}} = 0.834 \text{ms}^{-1} \]

It is evident that the difference between both velocities is subtle, so in further calculations the mean velocity will be used:

\[ w = \frac{(0.853 + 0.834)}{2} = 0.844 \text{ms}^{-1} \]

So, the column diameter could be found, using eq. (6):

\[ D = \frac{4.581}{\sqrt{\pi 0.844 2.79}} = 1.77 \text{m} \]

Here 2.79 kg m\(^{-3}\) is the mean vapour density in the column and 5.81 kg s\(^{-1}\) is the mean mass flow rate in the column.

After the standardising we find the standard diameter to be D = 1.8 m, so the vapours’ velocity after correction will be:

\[ w = 0.844 \left(\frac{1.78}{1.8}\right)^2 = 0.82 \text{ms}^{-1} \]

For the standard column diameter of 1800 mm we can find the perforated plate of following parameters [11]:

- Plate hole’s diameter, \(d_o\)..................8 mm
- Distance between holes, t..................15 mm
- Weir height, \(h_w\)..................30 mm
- Weir width, \(b\)..................1050 mm
- Plate free section, \(F\)..................18.8 %
- Plate operation section, \(S_r\)...........2.294 m\(^2\)

The working vapour velocity is:

\[ w_r = \frac{w S_r}{0.785 D^2} = 0.82 \frac{0.785 1.8^2}{2.294} = 0.91 \text{ms}^{-1} \]

Column height calculation.

It was already mentioned that the number of theoretical plates could be found graphically and then corrected by use of plate efficiency coefficient. The number of theoretical plates was found to be 21.7. The mean plate efficiency found by eq.(10) and fig. 3 is 0.72. Here the relative volatility was found to be approximately 2.5. So the real plate number is 30.14, or 31. The column height, found by eq.(12) is 16.2 m.

Now the full column weight has to be found in order to calculate the column support and basement (see Fig. 4). It consists of all column elements’ mass and the mass of liquid on the plates. The elements masses are summarised in Table 2.
Total mass: 16110.0 kg + 5 % for weld and fittings 805.5 kg = 16915.5 kg
Total weight: 7904.0 N = 165975N
Taking into account the liquid volume on the plate and its mean density, the total liquid mass in the column was found to be 1700 kg. So, the empty column mass was given, the full column mass is 16915.5 + 1700 = 18615.5 kg or the full column weight is 18.27 × 10^4 N.

All these data are necessary to be able to calculate the column support. For this purpose the calculations’ method, presented in [12] was used. The open air case was supposed. So, the atmosphere conditions had to be taken into account (especially wind force). The data for the calculations are:
- Type of the apparatus - vertical, cylindrical steel column;
- outdoor mounted apparatus;
- outer diameter - 1.832 m;
- support height H_s = 1 m;
- Full column height

\[ H = H_s + H_p + 2H_d + H_e = 16.2 + 1 + 0.06 + 0.24 = 17.5 m \]

Full column weight \( G = 18.27 \times 10^4 N \)

Empty column weight \( G_i = 16.60 \times 10^4 N \)
support material S3 (S355K2G2W [13])

\[ [\sigma] = 146.10^6 Nm^{-2}; \quad \sigma_y = 240.10^6 Nm^{-2}; \]

\[ E = 205.10^9 Nm^{-2}; \]

Here \([\sigma]\) is the limit bending stress for the material; \(\sigma_y\) is the yield stress of the material; \(E\) is the elasticity modulus.

The support is mounted on a concrete seating. The wind stability factor for cylindrical apparatuses has to be found, following the well established method [12]:
Both coefficients used in calculations are: \(k_1 = 0.7\) for cylindrical apparatus; \(k_2 = 2\) - dynamic coefficient depending on height-to-diameter ratio

\[ H/D = 17.5/1.832 = 9.55 \geq 5 \rightarrow k_2 = 2 \]

The wind stability moment was found to be:

\[ M_w = 0.5k_1k_2q_wH^2D_{out} = 0.5 \times 0.7 \times 2 \times 10^3 \times 17.5^2 \times 1.832 = 392735Nm \]

(12)

Here \(q_w\) is a relative wind charge \(q_w = 10^3 Pa\)
The support wall was chosen to has 0.01 m thickness (outer diameter of the column being \(D_{out} = 1.832 m\)).

Checking up the support stability.
- At first the bending stresses in the support wall were to be checked up.

\[ \sigma = \frac{GD_{out} + 4M_b}{\pi D^3 s} = \frac{18.27 \times 10^4 \times 1.832 + 4.39 \times 28.10^4}{\pi \times 1.832^3 \times 0.01} = 18.10^6 < 146.10^6 Pa \]

(13)

\[ k = \frac{2M_b}{0.25GD + M_b} = \frac{2.39 \times 28.10^4}{0.25 \times 18.27 \times 10^4 \times 1.832 + 39.28 \times 10^4} = 1.648 \rightarrow 1.65 \]
Table 2. Calculations of total mass of full distillation column.

<table>
<thead>
<tr>
<th>No</th>
<th>Detail</th>
<th>Number</th>
<th>mass per unit, kg</th>
<th>mass found from</th>
<th>total mass, kg</th>
<th>total weight, G=mg, N</th>
<th>note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>plate</td>
<td>31</td>
<td>115</td>
<td>literat. data [11]</td>
<td>3565</td>
<td>34980</td>
<td>stainless steel,</td>
</tr>
<tr>
<td>2</td>
<td>weir</td>
<td>31</td>
<td>calculated</td>
<td></td>
<td>46</td>
<td>451</td>
<td>same</td>
</tr>
<tr>
<td>3</td>
<td>column</td>
<td>1</td>
<td>12030</td>
<td>calculated</td>
<td>12030</td>
<td>118038</td>
<td>H=16.2 m; s=16mm</td>
</tr>
<tr>
<td>4</td>
<td>cover/bottom</td>
<td>2</td>
<td>143</td>
<td>literat. data [12]</td>
<td>286</td>
<td>2806</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>flanch</td>
<td>2</td>
<td>78.5</td>
<td>calculated</td>
<td>150</td>
<td>1472</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>bolts, screw-nuts, washers</td>
<td>2x40 =80</td>
<td></td>
<td></td>
<td>32.48</td>
<td>318</td>
<td></td>
</tr>
</tbody>
</table>

The stability requirement is:

\[
\sqrt{k_1 \left(1 - k_2^2\right) + 0.125 \cdot k_2} \left(G + \frac{4M_b}{D}\right) \frac{1}{E} = \]

\[
= \sqrt{1.8 \left(1 - \frac{1.65}{2}\right) + 0.125 \cdot 1.65 \cdot 6.8} \cdot \frac{1}{\sqrt{18.27 \cdot 10^4 + 439.28 \cdot 10^4}} = 0.00295m = 0.003m
\]

So, it is evident, that 0.003 m < S = 0.01 m and the construction stability is assured.

To finish the support calculations is necessary to calculate the dimensions of basement disc:

\[D_2 = D_{out} - 2.0.03 = 1.832 - 0.06 = 1.772m \tag{16}\]

The outer basement disc diameter is:

\[D_1 = D_{out} + 2s + 2l = 1.832 + 2.0.01 + 2.0.08 = 2.012m \tag{17}\]

here \(l\) is the dimension, presented in Fig. 4.

The maximal basement crushing stress is:

\[
\sigma_{\text{max}} = \frac{4G}{\pi \left(D_1^2 - D_2^2\right)} + \frac{M_b}{0.1 \left(D_1^4 - D_2^4\right)} = 1.46 \cdot 10^6 Pa < q = 2.2 \cdot 10^6 Pa
\]

The thickness of basement disc was supposed to be \(S_d = 0.014 m\). Now the minimal basement crushing stress must be calculated:

\[
\sigma_{\text{min}} = \frac{4G}{\pi \left(D_1^2 - D_2^2\right)} - \frac{M_b}{\left(D_1^4 - D_2^4\right)} = -0.98 \cdot 10^6 Pa \tag{19}
\]

This means that the apparatus would be unstable so the basement screws have to be used. The general condition of basement screws charge is:

\[
P'_s = \frac{\pi}{4} \left(D_1^2 - D_2^2\right) \sigma_{\text{min}} = 70.10^4 N \tag{20}
\]

The basement screws chosen are M30/S355K2G2W. Their number is 8.

CONCLUSIONS

The idea for joint project in Chemical Engineering/Applied Mechanics has been demonstrated. The calculations of distillation column and the mechanical support and basement were done. It is evident that this is a way to enlarge the students engineering knowledge. As a result of such interdisciplinary co-operation an enhancement of level of knowledge of the students could be expected, consisted in closing the cycle from chemi-
Engineering project calculations to mechanical calculations and preparing the complete engineering documentation for the equipment. If possible to complete this material with economical estimation, this could successfully be a for-diploma project for MSc students in Chemical Technologies and Chemical Engineering.

REFERENCES