

Individual Detailed Design Report

Node 4 — Pectin Purification and Ethanol Recovery

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Executive Summary

Conserve Consultancy have designed a pectin manufacture process to produce pectin from raw orange peels. The process produces approximately 142 tonnes of pectin per annum, which is integrated into the jam manufacturing process as well as sold as a powdered product.

The following report describes Node 4 of the process, in which pectin purification and ethanol recovery occurs. An ethanol recovery of 95 wt.% has been achieved by means of a continuous operation distillation column (D-401). A column diameter and column height of 1.40 metres and 7.50 metres respectively have been chosen for the final column specification, and a skirt support structure has been designed to withstand the pressure, dead weight and bending stresses associated with the unit. The construction of the column will require additional internal equipment, including 21 valve plates which have also been designed in this report. The implementation of recovery column D-401 significantly reduces the required feedstock ethanol from 4420 tonnes per annum to 221 tonnes per annum. Taking the price of ethanol as \$0.5/kg, this equates to a saving of approximately \$2 million per annum.

This report also includes detailed specification sheets for every major unit in Node 4, engineering drawings for the distillation column and valve plates, and a piping and instrumentation diagram to show how Node 4 will be operated and controlled.

Node 4 requires a total capital cost of \$4 million, with an accuracy of ± 30 per cent. The operating costs of the Node are \$450,000 per annum and the cost of feedstock ethanol per annum is \$110,000. Revenue from pectin sales are expected to be \$3.5 million per annum. This gives a yearly profit of approximately \$2.9 million for Node 4 - however this does not take into account the energy requirements by the node, which are supplied by Node 5, nor the raw material costs associated with Node 3.

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1 Introduction

Conserve Consultancy's pectin manufacturing process produces approximately 142 tonnes of pectin per annum. The manufactured pectin is mixed with the fruit and sugar solution in the jam manufacturing process to coagulate the final mixture. The remaining pectin is sent to storage where it is sold.

In the previous A3 Scheme Report and A3 Mass and Energy Balance Report, an overview of the entire process was presented. This process has since split into five nodes. In this report, Node 4 has been selected for detailed analysis and specification of its process units, process control, and an economic analysis. A detailed design has also been conducted on the ethanol recovery distillation column in the node, allowing a detailed specification of the unit.

This report will focus on the pectin purification after extraction and the recovery of ethanol used in the purification process via distillation column apparatus.

2 Overview of Pectin Manufacturing:

2.1 Node 3 - Essential Oils Production and Pectin Extraction

Node 3 begins with the processing of the flavedo of the orange peel. The peels are manually emptied into a screw press alongside water – the shearing action from the screw onto the peels releases the valuable essential oils from the orange flavedo (Hull et al., 1953). This water and oil emulsion is fed into a train of centrifuges – the first centrifuge acts at a high force to remove the approximately 56 wt.% of the water (Hull et al., 1953). A second centrifuge is then used to increase the concentration of the essential oils in the stream to 99 wt.% by the further removal of water. The stream of oils is then cooled to -15°C allowing the cold pressed oil to solidify - a final centrifuge is used to separate the cold pressed oil from the oil stearoptene (the very valuable portion of the oil) before both oils are sent to storage (Hull et al., 1953).

The orange peel that was separated from the flavedo of the peel in the screw press stage is fed into a shredder via a screw conveyer - here the peels are reduced to approximately 2 mm in length to increase the surface area available for acid hydrolysis (Casas-Orozco et al., 2015). The shredded peels are then fed into an acid hydrolysis tank with hydrochloric acid - here the mixture is agitated and heated to convert the insoluble protopectin in the peel into soluble pectin (Casas-Orozco et al., 2015). A filter train is used to remove the majority of the remnant solid peel. The filtered pectin solution is further fed into an evaporator to evaporate all of the hydrochloric acid as well as a large quantity of water in the product (Hull et al., 1953). This is done to reduce the size of the downstream units in Node 4, further reducing the capital cost of the plant. The acid vapours are further condensed and recycled as a feedstock in the acid hydrolysis step.

2.2 Node 4 - Pectin Purification and Ethanol Recovery

Node 4 involves the purification of the previously extracted pectin in Node 3. The purification stages first take place inside two parallel precipitation tanks - the pectin feed is mixed with ethanol in a 2:1 (v/v) solvent ratio (Casas-Orozco et al., 2015). The ethanol is used to coagulate the pectin into a gel-like substance - pectin is insoluble in ethanol, so upon mixing it precipitates out of solution as a gel. This leaves the majority of the impurities in the solution (Garna et al., 2007). The gelled pectin is next pumped into a washing tank train consisting of two washing tanks where concentrated ethanol solvent is again mixed with the precipitated gel to wash the final pectin product. Impurities removed include mono and disaccharides and acid remnants from the hydrolysis stage in Node 3 (Casas-Orozco et al., 2015). Each washing tank cycle lasts 30 minutes to ensure the impurities are removed, and that the pectin has an acid content of above

pH 4 so that the pectin does not decompose in the further downstream processing (Casas-Orozco et al., 2015; Shi et al., 1996).

The washed gel is sent to a mechanical press, where approximately 50 wt.% of the liquid is removed from the gel (Casas-Orozco et al., 2015). A belt conveyor dryer is used to dry the pressed pectin gel to a moisture content of 5 wt.% before it is milled into a fine white powder. Due to the large quantity of ethanol used in the purification stages, distillation column apparatus has been implemented to recover a large quantity of ethanol - this ethanol is then recycled as a feedstock for the precipitation and washing stages.

Figures (1) and (2) show a Gantt charts for the batch time of the whole pectin process at start-up and full operation respectively. As the Gantt chart shows, each batch cycle to produce pectin takes proximately 8 hours per batch, with opportunity to increase and decrease production rate due to the possibility of overlapping cycles. With three cycles per day, 990 cycles per annum can be conducted. This equates to the production of 144 tonnes of pectin per annum (see Section (E) in Appendices).

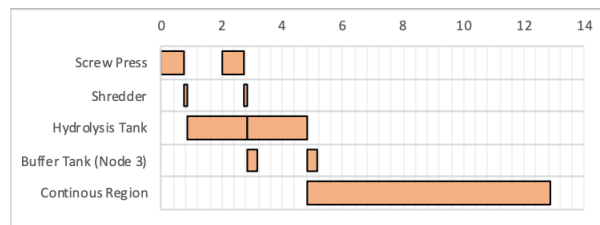


Figure 1: Gantt chart of pectin batch time at start-up.

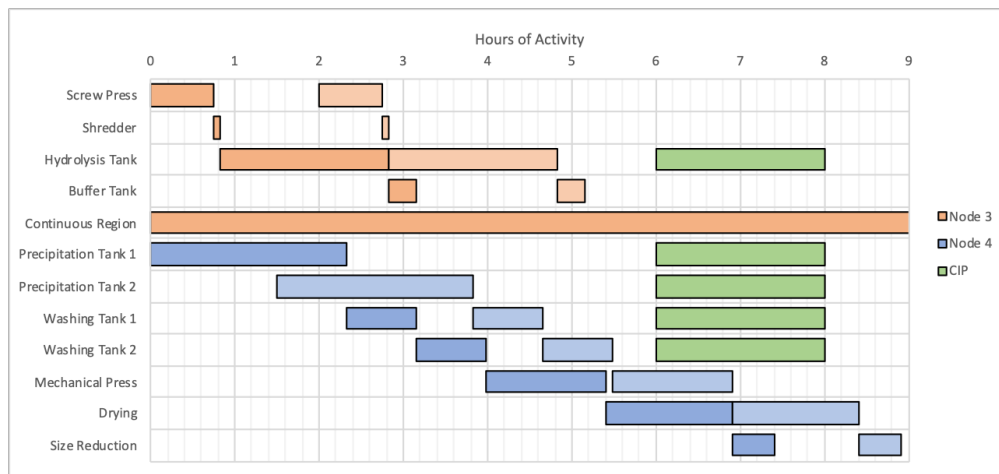


Figure 2: Gantt chart of pectin batch time at full operation.

3 Detailed Design Specification Sheets

| <i>DP3 Specification Sheet</i> | | Written By: | Samuel Ellis |
|---------------------------------------|--|--------------------|---------------------|
| Plant: | Pectin Production | Item: | Distillation Column |
| Node: | 4 – Pectin Purification and Ethanol Recovery | ID Tag: | D-401 |
| 1. Operation | mode | continuous | |
| | conditions | 353 | K |
| | | 101 | kPa |
| 2. Flow | (a) feed - temperature | 350 | K |
| | pressure | 1 | bar |
| | viscosity | 0.447 | cP |
| | density (liquid) | 762 | kg/m ³ |
| | (b) bottoms - temperature | 372 | K |
| | pressure | 1 | bar |
| | viscosity | 0.447 | cP |
| | density (liquid) | 955 | kg/m ³ |
| | (c) overhead - temperature | 360 | K |
| | pressure | 1.43 | bar |
| | viscosity | 0.447 | cP |
| | density (liquid) | 736 | kg/m ³ |
| 3. Dimensions | (a) column - height | 7.50 | m |
| | - inside diameter | 1.40 | m |
| | - shell/wall thickness | 11 | mm |
| | (b) trays - number of trays | 21 | - |
| | - type | valve | - |
| | - spacing | 0.3 | m |
| | (c) support - type | skirt | - |
| | - height | 1.0 | m |
| | (d) insulation - thickness | 50 | mm |

| | | | |
|------------------------------------|-----------------------|---------------------|-----|
| 4. Material of Construction | (a) shell | 304 stainless steel | |
| | (b) trays | 304 stainless steel | |
| | (c) support | carbon steel | |
| | (d) insulation | mineral wool | |
| 5. Operating Data | (a) ΔP column | 0.206 | bar |
| | (b) % flooding | 71 | |

| | | | |
|---------------------------------------|--|---------------------|--------------|
| <i>DP3 Specification Sheet</i> | | Written By: | Samuel Ellis |
| Plant: | Pectin Production | Item: | Valve Plate |
| Node: | 4 – Pectin Purification and Ethanol Recovery | ID Tag: | VP-401 |
| 1. Dimensions | (a) plate inside diameter | 1.40 | m |
| | (b) hole size | 5 | mm |
| | (c) hole pitch | 13 | mm |
| | (d) total holes | 4000 | |
| | (e) active holes | 4000 | |
| | (f) turn-down | 70% of max rate | |
| | (g) plate spacing | 0.3 | m |
| | (f) plate thickness | 0.5 | mm |
| | (h) unperforated edge strip width | 50 | mm |
| | (i) calming zone width | 50 | mm |
| | (j) plate pressure drop | 106 | mm liq |
| 2. Material of Construction | (a) plate material | 304 stainless steel | |
| | (b) downcomer material | mild steel | |

4 Detailed Design of Distillation Column D-401

4.1 Introduction

Distillation column D-401 is utilised to recover a large proportion of the ethanol used in the precipitation and washing stages. The feed into this column consists of water, ethanol, a soluble sugars mixture, as well as small quantities of pectin and hydrochloric acid. The column is designed to increase the concentration of ethanol from 75% v/v to 96% v/v. The distillate is then mixed with a make-up stream of 96% v/v ethanol and a small water make-up in an auxiliary mixing tank to create the desired ethanol concentration of 88% v/v for use in the precipitation and washing stages.

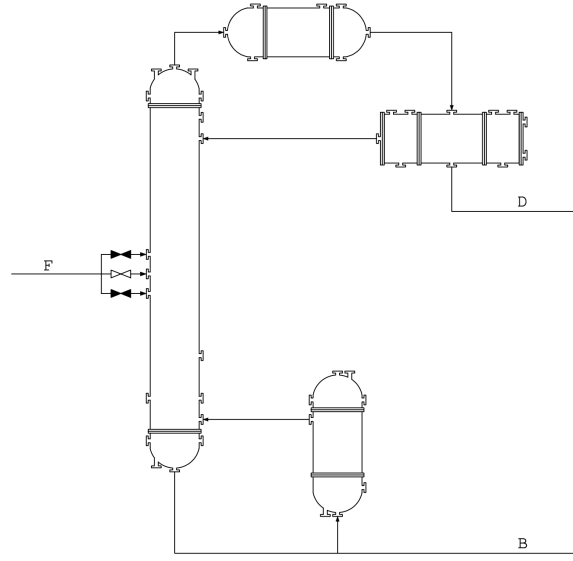


Figure 3: Distillation Column Schematic.

4.2 Revised Mass Balance

Due to the nature of the precipitation and washing stages operating batch-wise before the distillation column in Node 4, every four hours the ethanol required to process one batch of pectin is required from the distillation column. Table (1) gives the flowrates and composition of the feed entering D-401.

Table 1: Flowrate and Composition Data for Distillation Column D-201.

| Component | Feed | | Bottoms | | Distillate | |
|--------------|----------------------|-------------|----------------------|-------------|----------------------|-------------|
| | Flowrate (kmol/h) | mol. % | Flowrate (kmol/h) | mol. % | Flowrate (kmol/h) | mol. % |
| Ethanol | 22.4 | 0.63 | 1.12 | 0.1 | 21.3 | 0.88 |
| Water | 12.6 | 0.35 | 9.69 | 0.86 | 2.87 | 0.12 |
| Other | 0.505 | 0.02 | 0.505 | 0.1152 | 0 | 0 |
| Pectin | 5.81E-06 | 0 | 5.81E-06 | 0.04 | 0 | 0 |
| Total | 35.5 | 1.00 | 20.1 | 1.00 | 18.2 | 1.00 |

4.3 Operating Conditions

The operating conditions for the distillation column include mode of operation (batch or continuous) and the column pressure. Due to the large quantity of ethanol being stripped in the column, a continuous column design has been selected, as well as to maintain a high level of efficiency due to the lack of continuous cleaning and adjusting to the system (Costello, 2016).

4.4 Minimum Number of Stages (Fenske Equation)

The minimum number of stages (N_{min}) in the distillation column is determined using the Fenske equation detailed in Equation (1) (Sinnott and Towler, 2020a):

$$N_{min} = \frac{\log \left[\frac{x_{lk}}{x_{hk}} \right]_d \left[\frac{x_{hk}}{x_{lk}} \right]_b}{\log \alpha_{avg}} \quad (1)$$

Where x_{lk} and x_{hk} are the light and heavy key concentrations respectively, and α_{avg} is the average relative volatility of the light key with respect to the heavy key (Sinnott and Towler, 2020a).

To calculate the average relative volatility of the system, the vapour-liquid equilibrium ratio (K-value) of the light-key and heavy-key components are required. The Wilson correlation is used to determine the equilibrium constant for the light and heavy components (Wilson, 1968):

$$K_i = \frac{P_{ci}}{P} \exp \left[5.37(1 + \omega_i) \left(1 - \frac{T_{ci}}{T} \right) \right] \quad (2)$$

Using the K-values determined in Equation (2) for the light and heavy key, the relative volatility (α_{lk}) can be calculated at the top and bottom of the column:

$$\alpha_{lk} = \frac{K_{lk}}{K_{hk}} \quad (3)$$

From the relative volatilities found using Equation (3), the average relative volatility can be determined using Equation (4):

$$\alpha_{avg} = (\alpha_{lk,top} \cdot \alpha_{lk,bot})^{0.5} \quad (4)$$

The MATLAB function `rel_vol.m` was used to compute the relative volatility of ethanol relative to a water-glucose solution, at an operating pressure of 101 kPa and an operating temperature at the top and bottom of the column of 355 K and 368 K respectively. Table (2) shows the calculated K-values and relative volatilities from the `rel_vol` function:

Table 2: Calculated equilibrium constants and relative volatilities using the Wilson correlation and `rel_vol` function (Wilson, 1968).

| Column Position | K_{lk} | K_{hk} | α |
|-----------------|----------|----------|----------|
| Top | 1.19E-03 | 5.78E-04 | 2.06 |
| Bottom | 1.88E-03 | 9.24E-04 | 2.03 |

The average relative volatility can be calculated using the relative volatility values shown in

Table (2):

$$\alpha_{avg} = (2.06 \cdot 2.03)^{0.5} \approx 2.05 \quad (5)$$

Substituting the average relative volatility into Equation (1) alongside the molar compositions found in Table (1) gives the minimum number of stages required in the column:

$$N_{min} = \frac{\log\left(\frac{21.3}{2.87}\right)\left(\frac{9.69}{1.12}\right)}{\log 2.05} \approx 6 \text{ stages} \quad (6)$$

4.5 Minimum Reflux Ratio (Underwood Equation)

The minimum reflux ratio (R_{min}) is determined using the Underwood equation (Sinnott and Towler, 2020a):

$$R_{min} + 1 = \sum \frac{\alpha_i \cdot x_{i,d}}{\alpha_i - \theta} \quad (7)$$

Where α_i is the relative volatility of component i with respect to water, $x_{i,d}$ is the molar composition of component i in the distillate, and θ is the root of the equation. The value of θ is linked to the q value (the ratio of heat required to vaporise one mole of feed and the molar latent heat of feed) by Equation (8) (Sinnott and Towler, 2020a):

$$q - 1 = \sum \frac{\alpha_i \cdot x_{i,f}}{\alpha_i - \theta} \quad (8)$$

Where $x_{lk,f}$ is the molar composition of ethanol (the light-key) in the feed. To find q , the MATLAB function `findq.m` was developed for an operating pressure of 101 kPa and a feed temperature of 343 K. The `findq.m` outputs the method shown in Equation (9):

$$q = \frac{H_v - H_f}{H_v - H_l} = \frac{1300 - 350}{1300 - 250} = 0.905 \quad (9)$$

Substituting q into Equation (8) yields:

$$\sum \frac{\alpha_i \cdot x_{i,f}}{\alpha_i - \theta} = 0.905 - 1 = -0.095 \quad (10)$$

To find θ , the `findtheta.m` function is used to determine an approximate theta for a given q value using Equation (8). The relative volatility of each component is found using the function `rel_vol.m`. Table (3) shows the tabulated results when using the `findtheta.m` function:

Table 3: Tabulated results from the `findtheta.m` function.

| Component | $x_{i,f}$ | α_i | $\alpha_i x_{i,f}$ | $\theta = 1.5$ | $\theta = 1.26$ |
|-----------|-------------|-------------|--------------------|-----------------|-------------------|
| Ethanol | 0.63 | 2.06 | 1.18 | 2.12 | 1.48 |
| Water | 0.35 | 1.0 | 0.41 | -0.824 | -1.58 |
| Other* | 0.02 | <i>neg.</i> | 0 | 0 | 0 |
| Pectin | <i>neg.</i> | <i>neg.</i> | 0 | 0 | 0 |
| | | | | $\Sigma = 1.30$ | $\Sigma = -0.105$ |

The inequality in Equation (8) has been solved for the root of the equation giving $\theta = 1.26$.

Substituting this parameter into Equation (7) gives the minimum reflux ratio. Table (4) shows the tabulated results using the MATLAB function `findRmin.m` and Equation (7):

Table 4: Tabulated results from the `findRmin.m` function.

| Component | $x_{i,d}$ | α_i | $\alpha_i x_{i,d}$ | $\alpha_i x_{i,d} / (\alpha_i - \theta)$ |
|-----------|-------------|-------------|--------------------|--|
| Ethanol | 0.88 | 2.06 | 1.85 | 2.33 |
| Water | 0.12 | 1.0 | 0.10 | -0.37 |
| Other* | <i>neg.</i> | <i>neg.</i> | 0 | 0 |
| Pectin | <i>neg.</i> | <i>neg.</i> | 0 | 0 |
| | | | | $\Sigma = 1.96$ |

This gives the minimum reflux ratio, $R_{min} + 1 = 1.96$, hence $R_{min} = 0.96$.

4.6 Actual Number of Theoretical Stages

To specify the number of theoretical stages in a distillation column, a specimen calculation is first required using the optimum reflux ratio (R_{opt}) for the column. As an initial approximation, the optimum reflux ratio will be taken as 150 per cent of the minimum reflux ratio calculated in Section (4.5) (Chhabra and BasavarajAnon, 2019).

$$R_{opt} = 1.5R_{min} = 1.5 \cdot 0.96 = 1.44 \quad (11)$$

4.6.1 Erbar-Maddox Correlation

The Erbar-Maddox correlation is a commonly used method to give reliable predictions of the number of actual stages in a distillation column (Chhabra and BasavarajAnon, 2019).

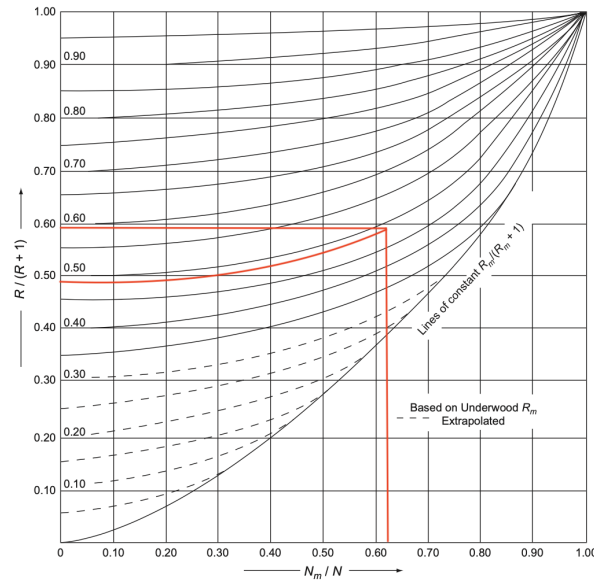


Figure 4: Erbar Maddox Correlation, taken from (Sinnott and Towler, 2020a).

The correlation shown in Figure (4) requires an estimate of the minimum reflux ratio and estimated optimum reflux to calculate the y-axis parameter:

$$\frac{R}{R+1} = \frac{1.44}{1.44+1} = 0.592 \quad (12)$$

$$\frac{R_{min}}{R_{min} + 1} = \frac{0.96}{0.96 + 1} = 0.492 \quad (13)$$

From the reflux gradients, the lines shown in Figure (4) can be constructed to return a N_{min}/N ratio of 0.62. The N_{min} value calculated in Section (4.4) can be substituted to determine the theoretical number of trays:

$$\frac{N_{min}}{N} = 0.62 \therefore N = \frac{6}{0.62} \approx 10 \text{ stages} \quad (14)$$

4.6.2 Molokanov Correlation

To verify the number of trays calculated by the Erbar-Maddox correlation, the Molokanov correlation is used to fit the Gilliland correlation to the following relation (Taylor and Kooijman, 2014):

$$Y = \frac{N - N_{min}}{N + 1} \quad (15)$$

$$X = \frac{R - R_{min}}{R + 1} \quad (16)$$

$$Y = 1 - \exp \left[\frac{1 + 54.4X}{11 + 117.2X} \left(\frac{X - 1}{X^{0.5}} \right) \right] \quad (17)$$

Equations (15-17) were solved in MATLAB using the built-in `vpasolve()` function. Table (5) shows the calculated X , Y and N variables in the Molokanov correlation using computed values of N_{min} and R_{min} from Sections (4.4) and (4.5) respectively:

Table 5: Tabulated results using the Molokanov equation.

| $N_{min} = 6, R = 1.44, R_{min} = 0.96$ | |
|---|---------------------|
| Y | $(N - 5)/(N + 1)$ |
| X | 0.197 |
| N | ≈ 12 stages |

Taking an average of the number of theoretical stages calculated in Sections (4.6.1) and (4.6.2) yields the final number of theoretical stages:

$$N = \frac{N_{Erbar} + N_{Molokanov}}{2} = \frac{10 + 12}{2} = 11 \text{ stages} \quad (18)$$

4.7 Overall Column Efficiency (O'Connell Relation)

The O'Connell correlation can be used to determine the overall column efficiency from the relative volatility of ethanol with respect to water (calculated in Section (4.4)) and average viscosity of the feed (Sinnott and Towler, 2020a). The O'Connell relation is shown in the form of an equation in (Eduljee, 1958):

$$E_o = 51 - 32.5 \log(\mu_{avg} \alpha_{avg}) \quad (19)$$

Table 6: Viscosity data for ethanol and water.

| | Ethanol | Water | Glucose |
|-----------------------------|-------------------------------|------------------------------|----------------------------|
| a | -7.37 | 2.41E-05 | - |
| b | 2770 | 248 | - |
| c | 74.7 | 140 | - |
| Relation | $a \cdot 10^{b/(T_{feed}-c)}$ | $\exp[a + b/(c + T_{feed})]$ | - |
| μ (mNs/m ²) | 0.478 | 0.401 | 0.520 (Telis et al., 2007) |

The viscosity of the feed can be evaluated at the feed temperature using the viscosity data in Table (6):

$$\mu_{avg} = x_{f,eth} \cdot \mu_{eth} + x_{f,wat} \cdot \mu_{wat} + x_{f,glu} \cdot \mu_{glu} \quad (20)$$

$$\mu_{avg} = 0.63 \cdot 0.478 + 0.35 \cdot 0.401 + 0.02 \cdot 0.520 \approx 0.447 \text{ mNs/m}^2 \quad (21)$$

The overall efficiency can now be determined from Equation (19):

$$E_o = 51 - 32.5 \log(0.447 \cdot 2.06) = 0.539 \quad (22)$$

4.7.1 Number of Actual Stages

The total number of actual stages can be calculated from the number of theoretical trays calculated in Equation (18) and the overall efficiency from the O'Connell relation:

$$N_{actual} = \frac{N_{theoretical} - 1}{E_o} = \frac{12 - 1}{0.539} \approx 21 \text{ stages} \quad (23)$$

Hence when the reflux ratio is 1.44, the number of actual stages (excluding the reboiler) in the distillation column is **21**.

4.8 Feed Point Location (Kirkbride Empirical Equation)

The Kirkbride empirical equation can be used to determine the feed point location on the distillation column (Kirkbride, 1968):

$$\log \left[\frac{N_r}{N_s} \right] = 0.206 \log \left[\left(\frac{B}{D} \right) \left(\frac{x_{f,wat}}{x_{f,eth}} \right) \left(\frac{x_{b,eth}}{x_{b,wat}} \right)^2 \right] \quad (24)$$

Using data from Table (1), Equation (24) can be solved:

$$\log \left[\frac{N_r}{N_s} \right] = 0.206 \log \left[\left(\frac{20.1}{18.2} \right) \left(\frac{0.35}{0.63} \right) \left(\frac{0.11}{0.86} \right)^2 \right] = -0.987 \quad (25)$$

$$\left[\frac{N_r}{N_s} \right] = 10^{-0.987} = 0.503 \quad (26)$$

Hence $N_r = 0.503N_s$. As $N_r + N_s$ must be equal to the number of actual stages (including the reboiler) calculated in Equation (23), the number of stages below the feed can be calculated:

$$0.1 = 503N_s + N_s = 1.50N_s = 21, \text{ so } N_s \approx 14 \text{ stages} \quad (27)$$

Therefore, the total number of stages below the feed (and hence the position of the feed point for separation), including the reboiler is stage 14. In practice, it is sensible to provide extra feed points around the predicted feed point to account for uncertainty in design calculations (Sinnott and Towler, 2020a). Accordingly, the distillation design will accommodate extra feed point locations on stage 13 and stage 15 to account for any design changes.

4.9 Pro/ii Simulation of D-401

Using the calculated values of the optimum reflux ratio, column efficiency and the actual number of stages calculated in Sections (4.6) and (4.7.1) respectively, the software Pro/ii was used to simulate the distillation column with more accurate design parameters. The simulation environment in Figure (5) details the parameters calculated using the software, which includes the condenser and reboiler duty, the reflux ratio, and temperature and pressure profiles of all inlet and outlet streams.

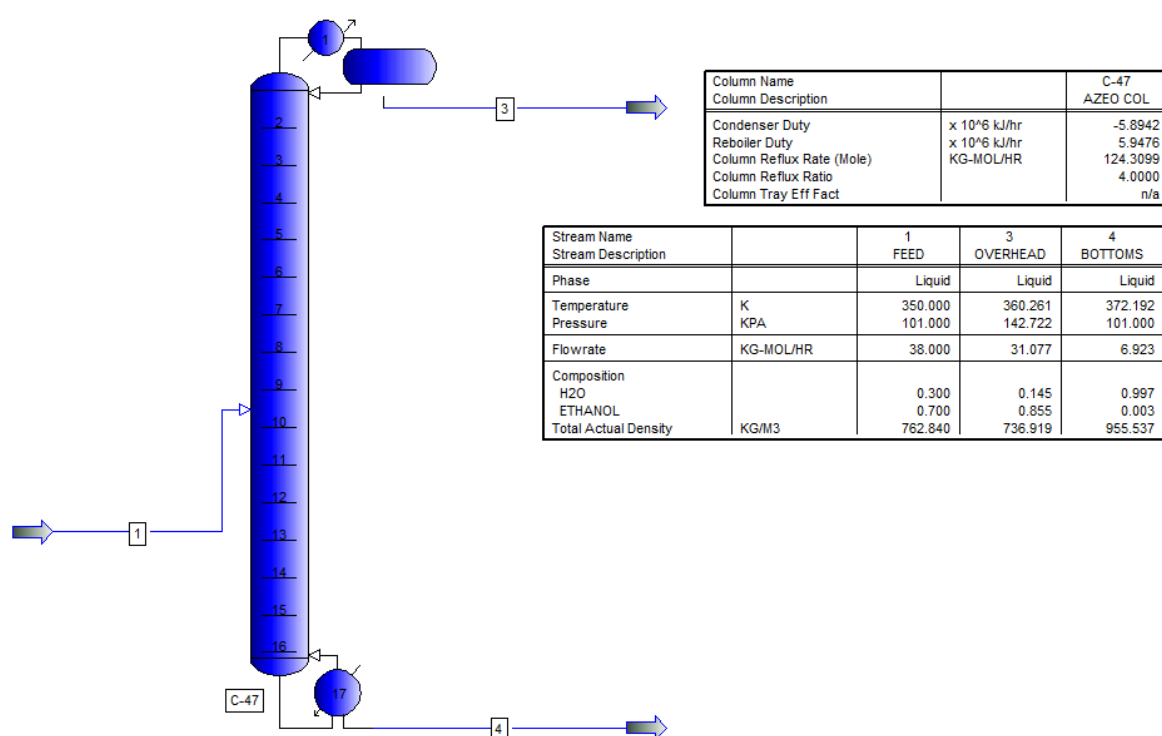


Figure 5: Pro/ii simulation using calculated the reflux ratio and number of actual trays.

4.10 Plate Design

The procedure for designing the plates in the distillation column will follow the methods presented in (Sinnott and Towler, 2020a). The procedure includes the following steps:

1. Calculate the maximum and minimum vapour and liquid flow-rates, for the turn-down ratio required.
2. Collect, or estimate, the system physical properties.
3. Select a trial plate spacing.
4. Estimate the column diameter, based on flooding considerations.
5. Decide the liquid flow arrangement.

6. Make a trial plate layout: downcomer area, active area, hole area, hole size, weir height.
7. Check the weeping rate, if unsatisfactory return to step 6.
8. Check the plate pressure drop, if too high return to step 6.
9. Check downcomer back-up, if too high return to step 6 or 3.
10. Decide plate layout details: calming zones, unperforated areas. Check hole pitch, if unsatisfactory return to step 6.
11. Recalculate the percentage flooding based on chosen column diameter.
12. Check entrainment, if too high return to step 4.
13. Optimise design: repeat steps 3 to 12 to find smallest diameter and plate spacing acceptable (lowest cost).
- 14 Finalise design: draw up the plate specification and sketch the layout (method taken from (Sinnott and Towler, 2020a)).

The plate has been designed using the MATLAB script `Plate_Design.m` located in Appendices H.6. The calculated values throughout Section (4.10) have been calculated using this script. The simulated Pro/ii values detailed in Section (4.9) will be used as the design parameters for the plates to increase the validity of the calculations.

4.10.1 Plate Type

The plate type chosen for use in the distillation column are valve plates. The vapour will pass through perforations in the plate whilst the liquid is retained on the plate by the vapour flow (Sinnott and Towler, 2020a). This plate type has been chosen due to their small capital cost and increased turndown performance compared to sieve plates (Sinnott and Towler, 2020a).

4.10.2 Collating System Properties

Assuming the pressure drop per plate in the column is 100 mm water, the pressure drop throughout the whole column can be determined using the number of plates calculated in Section (4.7.1), and hence the bottom operating pressure can be calculated:

$$\Delta P = \rho_w g h_w \cdot N_{actual} = 1000 \cdot 9.81 \cdot 0.1 \cdot 21 = 20600 \text{ Pa} \quad (28)$$

$$P_{bot} = P_{top} \cdot \Delta P = 101325 + 20600 = 122000 \text{ Pa} \quad (29)$$

The physical properties of the system were determined from a PRO/II simulation of the column detailed in Section (4.9). These system properties are outlined in Table (7) below:

Table 7: Physical system properties from the PRO/II simulation.

| Stream | Feed | Overhead | Bottoms |
|-------------------------------------|--------|----------|---------|
| Phase | Liquid | Liquid | Liquid |
| Temperature (K) | 350 | 360 | 372 |
| Liquid Density (kg/m ³) | 763 | 737 | 956 |
| Vapour Density (kg/m ³) | - | 2.03 | 2.03 |
| Molecular Weight (kg/kmol) | - | 44.6 | 69.0 |

4.10.3 Flooding Velocity

The flooding vapour velocity is required as an upper limit for the maximum vapour velocity. The flooding velocity can be estimated using the correlation given by (Sinnott and Towler, 2020a; Fair, 1963):

$$u_f = K_1 \sqrt{\left(\frac{\rho_l - \rho_v}{\rho_v} \right)} \quad (30)$$

Where u_f is the flooding vapour velocity (m/s) and K_1 is a constant determined from the liquid-vapour flow factor F_{LV} . This factor is given by Equation (31) (Sinnott and Towler, 2020a):

$$F_{LV} = \frac{L_w}{V_w} \sqrt{\frac{\rho_v}{\rho_l}} \quad (31)$$

Where L_w and V_w are the liquid and vapour molar flowrates (kmol/h) respectively. Assuming the feed is a saturated liquid, the molar flowrates can be calculated using the following relations, where F_i is the molar flowrate of stream i (kmol/h):

$$L_w = R_{opt} \cdot F_D = 4.00 \cdot 24.2 = 96.8 \text{ kmol/h} \quad (32)$$

$$V_w = (R_{opt} + 1) \cdot F_D = (4.00 + 1) \cdot 24.2 = 121 \text{ kmol/h} \quad (33)$$

$$F_{LV,top} = \frac{96.8}{121} \sqrt{\frac{2.03}{737}} = 0.0420 \quad (34)$$

$$F_{LV,bot} = \frac{96.8}{121} \sqrt{\frac{2.03}{956}} = 0.0369 \quad (35)$$

Using Figure (6), the constant K_1 can now be determined for the top and bottom plates of the column. Figure (6) is subject to the conditions that no foaming occurs in the column, and that the hole size in the perforated area is less than 6.5 mm (Sinnott and Towler, 2020a). A plate spacing of 0.3 metres is assumed in this calculation as an acceptable initial guess (Sinnott and Towler, 2020a).

This returns a value for the flooding constant K_1 of 0.065 at both the top and bottom of the column. Dependent on the hole:active area ratio and liquid surface tension in the system, the constant K_1 is subject to change. This has been accounted for in the `Plate_Design.m` script, which includes the following code to consider changes in plate construction and surface tension:

```
if A_hole/A_active_top >= 0.10
    K1_top = (K1_top*1.0)*(st_liq/0.02)^0.2;
    K1_bot = (K1_bot*1.0)*(st_liq/0.02)^0.2;
elseif A_hole/A_active_top >= 0.08 && A_hole/A_active_top < 0.10
    K1_top = K1_top*0.9*(st_liq/0.02)^0.2;
    K1_bot = K1_bot*0.9*(st_liq/0.02)^0.2;
elseif A_hole/A_active_top >= 0.06 && A_hole/A_active_top < 0.08
    K1_top = K1_top*0.8*(st_liq/0.02)^0.2;
    K1_bot = K1_bot*0.8*(st_liq/0.02)^0.2;
end
```

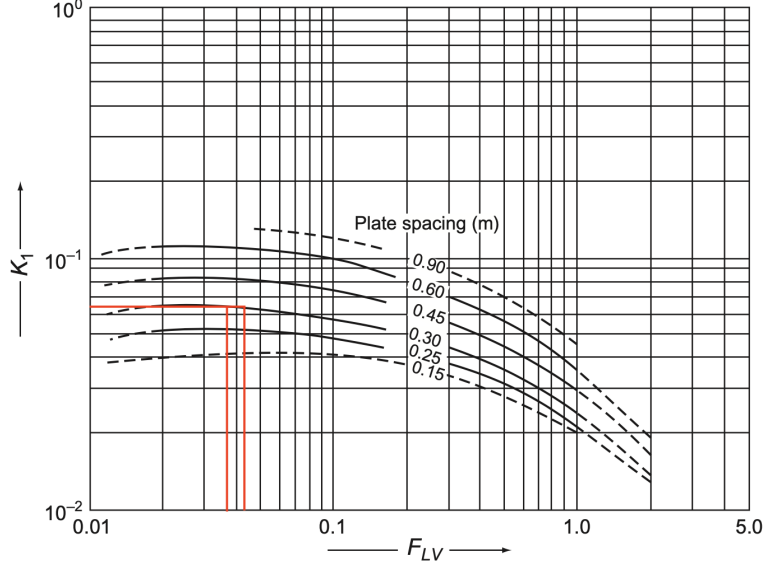


Figure 6: Flooding velocity of distillation plates. Graph taken from (Sinnott and Towler, 2020a).

The liquid surface tension is assumed to be 0.02 N/m and the hole:active area ratio is assumed to be 1.0. Using Equation (30), the flooding velocity at the top and bottom of the column can be calculated:

$$u_{f,top} = 0.065 \cdot \sqrt{\left(\frac{737 - 2.03}{2.03}\right)} = 1.24 \text{ m/s} \quad (36)$$

$$u_{f,bot} = 0.065 \cdot \sqrt{\left(\frac{956 - 2.03}{2.03}\right)} = 1.41 \text{ m/s} \quad (37)$$

It is common for a design velocity of 85 per cent of the flooding velocities calculated in Equations (36-37). Therefore, the top and bottom design velocities can be taken as:

$$u_{top} = 0.85 \cdot u_{f,top} = 1.05 \text{ m/s} \quad (38)$$

$$u_{bot} = 0.85 \cdot u_{f,bot} = 1.20 \text{ m/s} \quad (39)$$

4.10.4 Net Area for Vapour-Liquid Disengagement

The net area for vapour-liquid disengagement requires the design velocities determined in Section (4.10.3) and the maximum volumetric vapour flowrate at the top and bottom of the column. These flowrates is calculated using the vapour molar flowrate, V_w , and the physical properties of the system identified in Table (7):

$$Q_{top} = \frac{V_w \cdot M_{liq,top}}{3600 \cdot \rho_{v,top}} = \frac{121 \cdot 44.6}{3600 \cdot 2.03} = 0.738 \text{ m}^3/\text{s} \quad (40)$$

$$Q_{bot} = \frac{V_w \cdot M_{liq,bot}}{3600 \cdot \rho_{v,bot}} = \frac{121 \cdot 69.0}{3600 \cdot 2.03} = 1.14 \text{ m}^3/\text{s} \quad (41)$$

Hence the net area for vapour-liquid disengagement can be calculated:

$$A_{n,top} = \frac{Q_{top}}{u_{top}} = \frac{0.738}{1.05} = 0.703 \text{ m}^2 \quad (42)$$

$$A_{n,bot} = \frac{Q_{bot}}{u_{bot}} = \frac{1.14}{1.20} = 0.950 \text{ m}^2 \quad (43)$$

4.10.5 Column Diameter

An estimate of the cross-sectional area of the column is required to determine the diameter of the column. From the net area calculated in Section (4.10.4), the cross-sectional area of the distillation column can be determined. This requires an initial estimate for the downcomer area (the sections where liquid enters and leaves the plate) of the plate. As an initial estimate, it is safe to assume the downcomer area is approximately 12 per cent of the total area. To account for entrainment in the column, the `Plate_Design.m` script will produce a warning message in the event of excessive flooding. From this script, an extra 0.5 metres has been added to the column cross-sectional area to ensure satisfactory flooding conditions.

$$A_{c,top} = \frac{A_{n,top}}{0.88} = \frac{0.703}{0.88} + 0.5 = 1.30 \text{ m}^2 \quad (44)$$

$$A_{c,bot} = \frac{A_{n,bot}}{0.88} = \frac{0.950}{0.88} + 0.5 = 1.57 \text{ m}^2 \quad (45)$$

The distillation column will be designed to be only one diameter at the top and bottom of the unit, hence the net area at the bottom will be chosen as the diameter constraint, and the perforated area on the plates above the feed will be reduced. The diameter of the column can be found using the calculated bottom net area:

$$D_c = \sqrt{\frac{4A_{c,bot}}{\pi}} = \sqrt{\frac{4 \cdot 1.57}{\pi}} = 1.40 \text{ m} \quad (46)$$

4.10.6 Liquid Flow Arrangement

The plate-type chosen in Section (4.10.1) can now be verified using Figure (7) by (Sinnott and Towler, 2020a). This is dependent on the diameter of the column and the maximum volumetric flowrate of the liquid. The maximum flowrate of the liquid can be calculated by the following relation:

$$Q_{liq,max} = \frac{L_w \cdot M_{liq,bot}}{3600 \cdot \rho_{l,bot}} = \frac{96.8 \cdot 69.0}{3600 \cdot 956} = 0.003 \text{ m}^3/\text{s} \quad (47)$$

Plotting the diameter and maximum liquid flowrate on Figure (7) shows that cross flow single-pass valve plates can be used in the column.

4.10.7 Weir Length and Weir Height

A good initial guess for the weir length is approximately 77 per cent of the column diameter, which is equivalent to a downcomer area of 12 per cent of the total column area (Sinnott and Towler, 2020a). The relation between the downcomer area and the weir length can be determined using Figure (8).

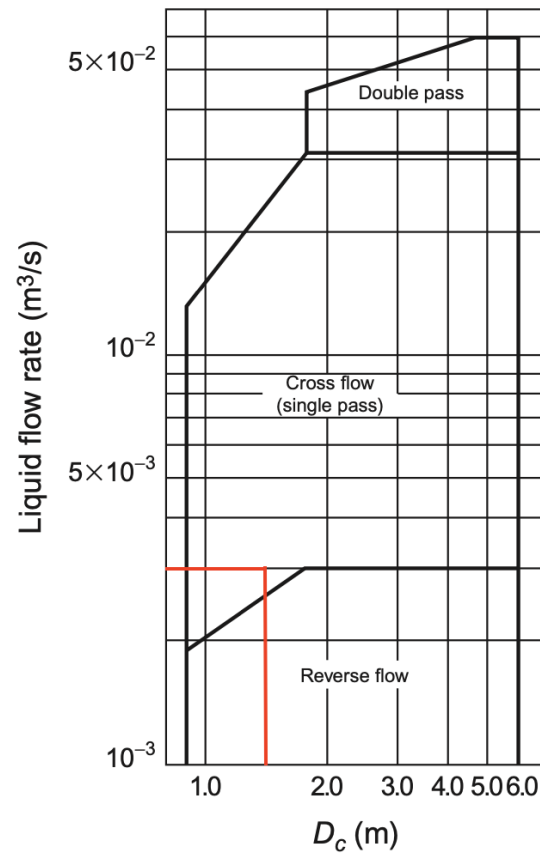


Figure 7: Liquid flow arrangement selection. Taken from (Sinnott and Towler, 2020a).

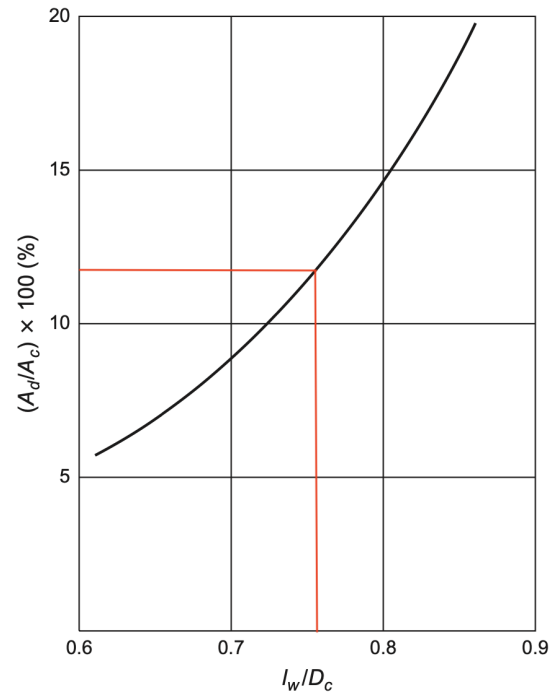


Figure 8: Downcomer area and weir length relationship. Taken from (Sinnott and Towler, 2020a).

Hence the weir length of the plates are given as:

$$l_w = 0.77 \cdot D_c = 0.77 \cdot 1.40 = 1.08 \text{ m} \quad (48)$$

The weir height has a significant effect on the efficiency of the column - larger weirs will increase the pressure drop across each stage but will also increase the efficiency of the column (Sinnott and Towler, 2020a). Therefore, the weir height chosen will be 50 mm as this is the recommended height for systems operating at (or above) atmospheric pressure (Sinnott and Towler, 2020a).

4.10.8 Trial Plate Design

The provisional plate design will use correlations relating the column dimensions to the plate dimensions. These correlations are given in Table (8) and (Sinnott and Towler, 2020a). Table (8) shows the initial plate design and dimensions, before any checks are conducted.

Table 8: Initial plate specification.

| Parameter | Correlation | Value | Units |
|------------------------|--------------|--------|----------------|
| Column diameter, D_c | D_c | 1.40 | m |
| Column area, A_c | A_c | 1.54 | m ² |
| Downcomer area, A_d | $0.24A_c$ | 0.377 | m ² |
| Net area, A_n | $A_c - A_d$ | 1.19 | m ² |
| Active area, A_a | $A_c - 2A_d$ | 0.786 | m ² |
| Hole area, A_h | $0.10A_a$ | 0.0786 | m ² |
| Weir length, l_w | Figure (8) | 1.08 | m |
| Weir height, h_w | - | 50 | mm |
| Hole diameter, d_h | - | 5 | mm |
| Plate thickness, t_p | - | 5 | mm |

4.10.9 Checking Weeping

Weeping occurs when the liquid leaking through the holes in the valve plates become significant. The velocity of the vapours at this ‘weep point’ is the minimum design velocity required for the correct operation of the column. One correlation for calculating the minimum design velocity is given in (Eduljee, 1958):

$$u_h = \frac{[K_2 - 0.90(25.4 - d_h)]}{(\rho_v)^{1/2}} \quad (49)$$

Where u_h is the minimum vapour velocity (m/s), d_h is the hole diameter (mm) and K_2 is a constant which depends on the depth of clear liquid on the plate. The constant K_2 is related to the minimum height of the weir liquid crest by Figure (9) (Sinnott and Towler, 2020a). The liquid crest height can be estimated using the Francis weir formula (Sinnott and Towler, 2020a):

$$h_{ow} = 750 \left[\frac{m_{liq,max}}{\rho_{liq,bot} l_w} \right]^{2/3} \quad (50)$$

Where h_i is the maximum or minimum liquid crest height (mm liq) and $m_{liq,max}$ is the maximum liquid mass flowrate (kg/s). The values of $m_{liq,max}$ can be determined from the liquid molar flowrate calculated in Equation (32). Assuming the minimum liquid mass flowrate $m_{liq,min}$ occurs

at 70 per cent turndown:

$$m_{liq,max} = \frac{L_w \cdot M_{bot}}{3600} = \frac{96.8 \cdot 69.0}{3600} = 1.86 \text{ kg/s} \quad (51)$$

$$m_{liq,min} = 0.70 m_{liq,max} = 0.70 \cdot 1.86 = 1.30 \text{ kg/s} \quad (52)$$

Using Equation (50), the maximum and minimum liquid crest heights can be estimated:

$$h_{ow,max} = 750 \left[\frac{1.86}{956 \cdot 1.08} \right]^{2/3} = 11.2 \text{ mm liq} \quad (53)$$

$$h_{ow,min} = 750 \left[\frac{1.30}{956 \cdot 1.08} \right]^{2/3} = 8.75 \text{ mm liq} \quad (54)$$

From Figure (9), the constant K_2 can be found. At the minimum rate, $h_w + h_{ow,min} = 50 + 8.75 \approx 59 \text{ mm liq}$.

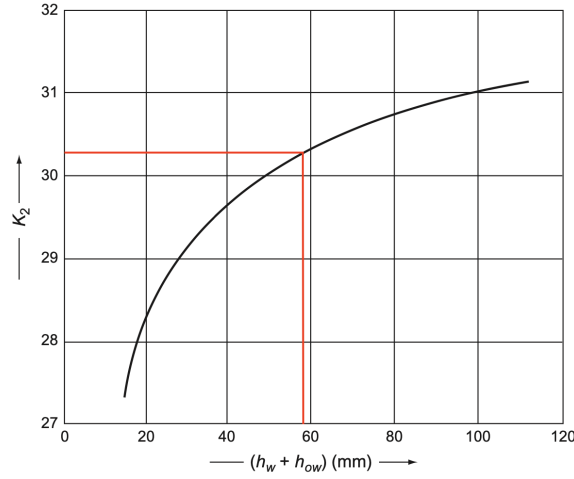


Figure 9: Weep point constant, correlated from the minimum liquid crest. Taken from (Sinnott and Towler, 2020a).

The minimum crest value returns K_2 as approximately 30.2. Using Equation (49), the minimum design velocity can now be determined:

$$u_h = \frac{30.2 - 0.90(25.4 - 5)}{(2.03)^{1/2}} = 8.31 \text{ m/s} \quad (55)$$

Comparing this to the actual minimum vapour velocity, which is calculated using the maximum volumetric flowrate at the bottom of the column, determined in Equation (41) at 70 per cent turndown and the total hole area using the correlation in Table (8):

$$u_{act} = \frac{0.7Q_{bot}}{A_h} = \frac{0.70 \cdot 1.14}{0.154} = 5.18 \text{ m/s} \quad (56)$$

Due to the actual minimum vapour velocity being smaller than the minimum weeping velocity calculated in Equation (55), this minimum rate will lead to weeping in the column and liquid will begin to leak through the perforations. The hole area must be reduced to increase the velocity of the vapour. The `Plate_Design.m` script utilises iteration to reduce the hole area until the velocity of the vapour is comfortably above the weeping point:


```

if u_vap_min_actual < u_vap_min_h
    X = ['Minimum operating rate leads to weeping at the bottom of the column.'];
    Y = ['Reduce hole area to 7 per cent of active area:'];
    disp(X); disp(Y)
    A_hole = 0.07*A_column;
    u_vap_min_actual = (0.70*Q_bot)/A_hole;
    if u_vap_min_actual < u_vap_min_h
        X = ['Minimum operating rate leads to weeping at the bottom of the column.'];
        Y = ['Reduce hole area to 5 per cent of active area:'];
        disp(X); disp(Y)
        A_hole = 0.05*A_column;
        u_vap_min_actual = (0.70*Q_bot)/A_hole;
    if u_vap_min_actual < u_vap_min_h
        X = ['Minimum operating rate leads to weeping at the bottom of the column.'];
        Y = ['Reduce hole area to 4 per cent of active area:'];
        disp(X); disp(Y)
        A_hole = 0.04*A_column;
        u_vap_min_actual = (0.70*Q_bot)/A_hole;
    end
end
else
end

```

This returns the actual minimum vapour velocity as 10.7 m/s, which is approximately 25 per cent above the weeping point, hence weeping will no longer occur in the column. This occurs when the hole area is reduced to 5 per cent of the total column area, which is approximately 0.077 m².

4.10.10 Plate Pressure Drop

The plate pressure drop used in Section (4.10.2) was assumed to be 100 mm of water pressure drop across each plate. Now that the vapour velocities are more understood, an accurate pressure drop across every plate can be calculated. The dry plate pressure drop can be calculated using Equation (57), where h_d is the dry plate drop (mm liq), C_o is the orifice coefficient and u_h is the maximum vapour velocity through the holes (m/s) (Sinnott and Towler, 2020a):

$$h_d = 51 \left[\frac{u_h}{C_o} \right]^2 \frac{\rho_{vap,bot}}{\rho_{liq,bot}} \quad (57)$$

The orifice coefficient C_o is obtained using Figure (10). This requires the ratio of the hole area A_h to the perforated (active) area A_a . Using the revised hole area in Section (4.10.9) and the active area from Table (8), the orifice coefficient can be found:

$$\frac{A_h}{A_a} = \frac{0.077}{0.786} = 0.098 \equiv 10 \quad (58)$$

The orifice coefficient for the system is found to be 0.84. The maximum vapour velocity through the holes can be calculated from the maximum volumetric flowrate, Q_{bot} :

$$u_h = \frac{Q_{bot}}{A_h} = \frac{1.14}{0.077} = 14.8 \text{ m/s} \quad (59)$$

Substituting these variables into Equation (57) yields the dry plate drop per plate:

$$h_d = 51 \left[\frac{14.8}{0.84} \right]^2 \frac{2.03}{956} \approx 34 \text{ mm liq} \quad (60)$$

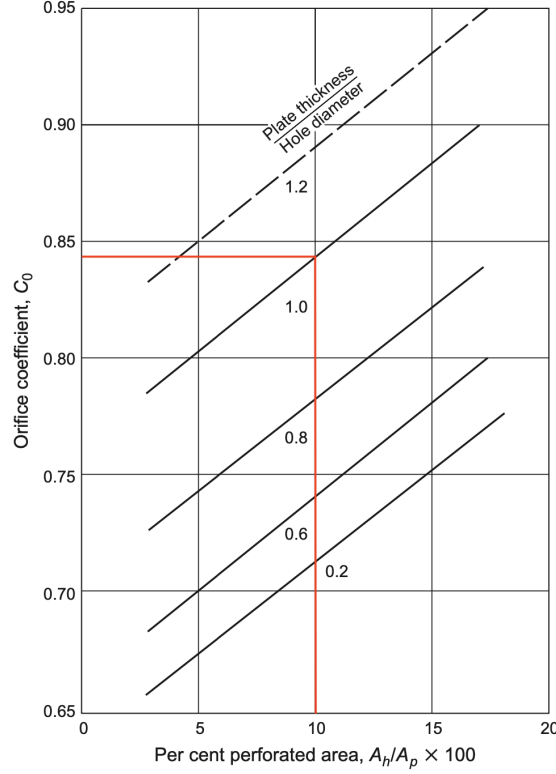


Figure 10: Orifice coefficient graph. Taken from (Sinnott and Towler, 2020a).

To calculate the total head, the residual head must also be considered. Equation (61) given by (Sinnott and Towler, 2020a) can be used to estimate the residual head drop:

$$h_r = \frac{12.5 \times 10^3}{\rho_{liq,bot}} = \frac{12.5 \times 10^3}{956} = 13.1 \text{ mm liq} \quad (61)$$

Hence the total pressure head per plate can be found by the summation of the individual pressure heads:

$$h_t = h_d + (h_w + h_{ow,min}) + h_r = 34 + (50 + 8.75) + 13.1 = 106 \text{ mm liq} \quad (62)$$

As 100 mm of liquid was used as an initial estimate of the pressure drop per plate, the calculation could be repeated with 106 mm of liquid to get a more accurate pressure profile, however this small change in the physical properties of the system will have little effect on the plate design, hence it can be ignored.

4.10.11 Downcomer Design (Back-Up)

The downcomer must be designed such that the level of the liquid in the downcomer is below the outlet weir on the plate above to prevent flooding of the column (Sinnott and Towler, 2020a). The clearance area under the downcomer (A_{ap}) is required to calculate the head loss in the downcomer. It is assumed that the height of the apron (h_{ap}) is set at 10 mm below the weir height at the outlet, hence the clearance area under the downcomer is calculated as:

$$h_{ap} = h_w - 10 = 50 - 10 = 40 \text{ mm} \quad (63)$$

$$A_{ap} = h_{ap} l_w = 40 \times 10^{-3} \cdot 1.08 = 0.0432 \text{ m}^2 \quad (64)$$

As this is lower than the calculated downcomer area shown in Table(8), this clearance area will be used to find the head loss in the downcomer (Sinnott and Towler, 2020a). This can be estimated using Equation (66), found in (Sinnott and Towler, 2020a):

$$h_{dc} = \frac{m_{liq,max}}{\rho_{liq,bot} A_{ap}} = \frac{1.86}{956 \cdot 0.0432} = 0.0450 \approx 1 \text{ mm liq} \quad (65)$$

Where h_{dc} is the head loss in the downcomer and $m_{liq,max}$ is the maximum liquid mass flowrate calculated in Equation (51). The length of the downcomer back-up (h_b) can be found by adding the total pressure head (h_t) from Equation (62), the weir height (h_w), the minimum weir crest ($h_{ow,min}$) and the downcomer head from Equation (66):

$$h_b = (h_w + h_{ow,min}) + h_t + h_{dc} = (50 + 8.75) + 106 + 1 = 166 \text{ mm} \quad (66)$$

To ensure safe design and operation of the column, the following inequality should be satisfied so that flooding in the column is avoided (Sinnott and Towler, 2020a):

$$h_b < 0.5(l_t + h_w) \quad (67)$$

Where l_t is the spacing between each tray in the column. Plate spacings usually range from 0.15 metres to 1 metre. (Sinnott and Towler, 2020a). For a column with diameter of 1.40 m, a plate spacing of 0.3 metres can be taken as an initial estimate. Hence the inequality becomes:

$$166 < 0.5(300 + 50) \quad (68)$$

The inequality in Equation (68) is true, therefore the chosen tray spacing of 0.3 metres is acceptable for the column. To ensure sufficient vapour disengagement from the liquid stream, a residence time of more than 3 seconds is required (Sinnott and Towler, 2020a). The downcomer residence time is given by the following relation:

$$\tau_r = \frac{A_d h_b \rho_{liq,bot}}{m_{liq,max}} = \frac{0.377 \cdot 166 \times 10^{-3} \cdot 956}{1.30} = 10 \text{ seconds} \quad (69)$$

4.10.12 Checking Entrainment

The liquid-vapour factor calculated in Equation (35) is required to determine the fractional entrainment from Figure (11). To calculate the percentage of flooding in the column, the actual vapour velocity (u_n) and flooding velocity from Section (4.10.3) are required:

$$u_n = \frac{Q_{bot}}{A_n} = \frac{1.14}{1.19} \approx 1 \text{ m/s} \quad (70)$$

$$\text{Flooding} = \frac{u_n}{u_{f,bot}} = \frac{1}{1.41} = 0.71 \quad (71)$$

Recalling that the value of F_{LV} was determined to be 3.69×10^{-3} in Section (4.10.3), the fractional entrainment is calculated to be 0.035 using Figure (11). As this is much smaller than the maximum fractional entrainment of 0.1, the effect of entrainment on the efficiency of the column can be neglected.

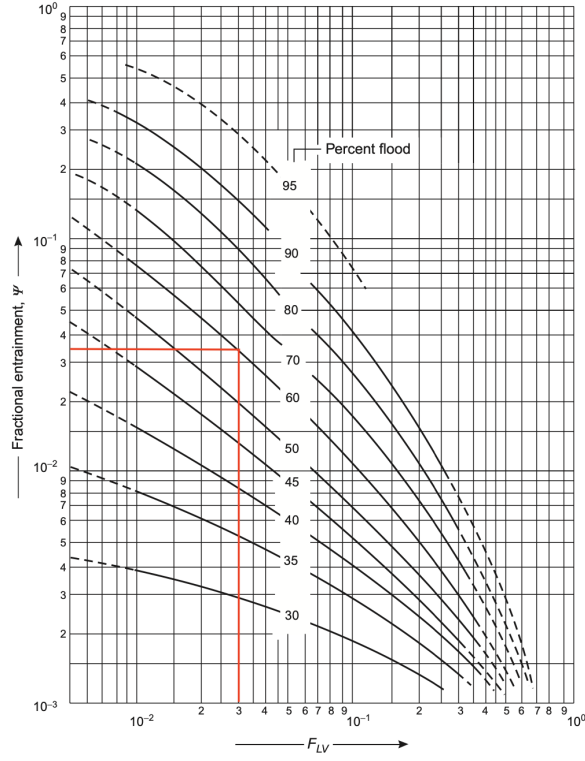


Figure 11: Graph of flooding percentage vs. fractional entrainment. Taken from (Sinnott and Towler, 2020a).

4.10.13 Perforated Area and Number of Holes

As the area available for perforation will be reduced by mechanical fittings and calming zones on the plate. Calming zones are unperforated strips of the plate at the inlet and outlet sides of the plate (Jaya, 2011). This will be 50 mm wide as this is the recommended zone size for the chosen diameter of the column (Sinnott and Towler, 2020a). To give structural integrity to the plates, a 50 mm unperforated strip will also be added around the edge of the plate.

Figure (12) shows the relationship between the chord angle (θ_c), chord height (l_h/D_c) and the chord length (l_w/D_c). The chord length can be determined from the length of the weir and column diameter specified in (8). This returns a chord length value of 0.77. This can similarly be done for chord height, returning a value of 0.18. These parameters are plotted on Figure (12) to return a chord angle of 87° . Hence the angle subtended by the edge of the plate will be 93° .

The lengths and areas of the unperforated edge strips (l_e , A_e) and calming zones (l_{calm} , A_{calm}) can now be determined, to find the total area available for perforations (A_p):

$$l_e = (D_c - t_e)\pi \frac{\theta_c}{180} = (1.4 - 50 \times 10^{-3})\pi \times 93/108 = 2.16 \text{ m} \quad (72)$$

$$A_e = l_e t_e = 2.16 \times 50 \times 10^{-3} = 0.108 \text{ m}^2 \quad (73)$$

$$l_{calm} = l_w + t_{calm} = 1.08 + 50 \times 10^{-3} = 1.13 \text{ m} \quad (74)$$

$$A_{calm} = 2(l_{calm} t_{calm}) = 2 \times (1.13 \times 50 \times 10^{-3}) = 0.113 \text{ m}^2 \quad (75)$$

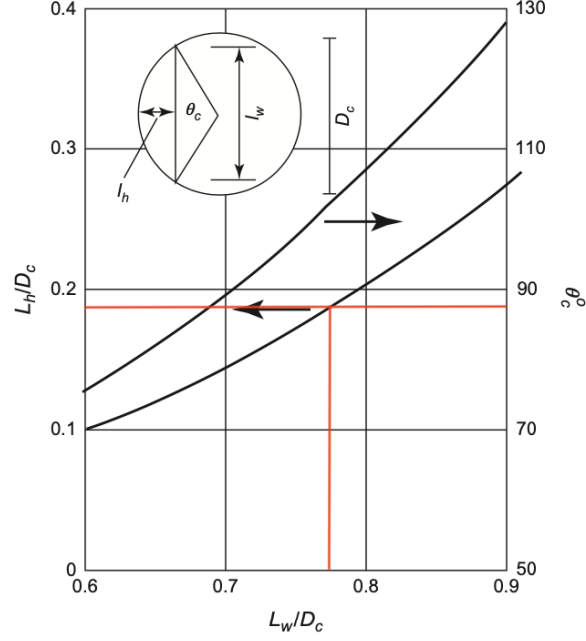


Figure 12: Graph showing relationship between chord length, height and angle. Taken from (Sinnott and Towler, 2020a).

$$A_p = A_a - A_e - A_{calm} = 0.786 - 0.108 - 0.113 = 0.565 \text{ m}^2 \quad (76)$$

The distance between the hole centres in the plate (l_p) must not be less than 2.0 hole diameters for effective distillation (Sinnott and Towler, 2020a). Within the range of 2.5 to 4.0 hole diameters is optimum selecting the number of active holes required on each plate. Equation (77) from (Sinnott and Towler, 2020a) can be used to verify the hole distance in the plate:

$$\frac{A_h}{A_p} = 0.9 \left[\frac{d_h}{l_p} \right]^2 \quad (77)$$

When the hole diameter d_h is 5 mm, Equation (77) can be rearranged and solved for l_p to give $l_p = 13$ mm. This is approximately 2.6 hole diameters which lies within the satisfactory range, hence the number of holes can be determined:

$$\text{Number of holes} = \frac{A_h}{\text{Area of one hole}} = \frac{0.0786}{1.964 \times 10^{-5}} \approx 4000 \text{ holes} \quad (78)$$

5 Mechanical Design of Distillation Column D-401

5.1 Column Height

The height of the column can be determined from utilising the actual number of stages (excluding the reboiler) calculated in Section (4.7.1), the plate spacing determined in Section (4.10.3) and the plate specifications detailed in section (4.10). Assuming the hemispherical heads of the distillation column each have a height of 0.5 metres to account for the fitting of additional equipment, the height of the column is:

$$L_c = N_{actual}(L_t + t_t) + (2H_h) = 21 \times (0.3 + 0.005) + (2 \times 0.5) = 7.5 \text{ m} \quad (79)$$

Where L_t is the length of the tray (m), t_t is the tray thickness (m) and H_h is the height of the hemispherical heads (m).

5.2 Wall Thickness

The parameters required to design the skirt of unit D-401 are shown in Table (9). It is assumed that the height of the skirt support is 1 metre, and that the thickness of the insulation around the column is approximately 50 mm thick. The column will be constructed from 304 stainless steel.

Table 9: Parameters required for skirt support design.

| Parameter | Value |
|---|-------------------------|
| Vessel, height (excluding heads) | 6.5 m |
| Vessel, diameter | 1.4 m |
| Skirt support, height | 1.0 m |
| Number of valve plates | 21 |
| Insulation, thickness | 50 mm |
| 304 stainless steel, maximum allowable stress | 120 N/mm ² |
| Operating pressure (bottom) | 0.122 N/mm ² |

5.2.1 Design Pressure

The design pressure of the column is taken as 10 per cent above the normal operating pressure at the bottom of the column. This is calculated in Equation (80), where P_c is the design pressure of the column in N/mm².

$$P_c = P_{op} \times 1.1 = 0.122 \times 1.1 = 0.135 \text{ N/mm}^2 \quad (80)$$

5.2.2 Minimum Wall Thickness

The wall thickness is calculated using Equation (120):

$$t_w = \frac{P_c D_c}{2SE - 1.2P_c} \quad (81)$$

Where S is the maximum allowable stress of stainless steel (N/mm²) and E is the welded joint efficiency. Table (9) shows the value of maximum allowable stress of 304 stainless steel, which is taken from (Sinnott and Towler, 2020b). It is assumed the welds will be fully radiographed, therefore the welded joint efficiency is equal to 1.0. With these values, the wall thickness can be determined:

$$t_w = \frac{0.135 \times 1.40 \times 10^3}{(2 \times 120 \times 1.0) - 1.2 \times 0.135} = 0.8 \text{ mm} \quad (82)$$

The wall thickness determined is lower than the minimum wall thickness (excluding corrosion allowance) of 7 mm defined in the ASME BPV Code Sec. VIII D.1 for a diameter of 1.4 metres (Sinnott and Towler, 2020b). Therefore the selected wall thickness of the column will be 7 mm, which will also accommodate 2 mm of corrosion resistance. As there will be more weight load at the bottom of the column, the wall thickness at the bottom of the column must be thicker than that at the top. As an initial estimate, the column will be divided into five sections of increasing wall thickness - starting at the top of the column, the wall thickness will be 7, 8, 9, 10 and 11 mm respectively.

5.2.3 Unit Weight

5.2.3.1 Shell Weight Equation (85) is used to calculate the vessel weight of a steel vessel (Sinnott and Towler, 2020b):

$$W_v = 240C_w D_m (H_v + 0.8D_m)t \quad (83)$$

Where W_v is the weight of the shell, excluding plates and fittings (N), C_w is a support factor which is 1.15 distillation columns, D_m is the mean diameter of the vessel (m) and H_v is the height of the vessel (m). As the thickness of the column varies throughout the column, an average thickness of 9 mm will be assumed for the calculations in this section. The mean diameter of the vessel can be calculated via Equation (84):

$$D_m = D_c + t \times 10^{-3} = 1.4 + 9 \times 10^{-3} = 1.409 \text{ m} \quad (84)$$

Hence the weight of the shell can be calculated using Equation (85) using data from Table (9):

$$W_v = 240 \times 1.15 \times 1.409 \times (6.5 + 0.8 \times 1.409) \times 9 = 27 \text{ kN} \quad (85)$$

5.2.3.2 Plate Weight The valve plates in the distillation column will also be constructed from 304 stainless steel. It is assumed that the weight of the liquid on each plates is 10 per cent of the weight of each plate. Using the plate specification parameters calculated in Section (4.10), the weight of the plates (W_p) can be calculated:

$$W_p = A_c N_{actual} \times 1.1 = 1.54 \times 21 \times 1.1 = 36 \text{ kN} \quad (86)$$

5.2.3.3 Insulation Weight The thickness of the insulation is shown in Table (9). Assuming that the type of insulation is mineral wool ($\rho_i = 130 \text{ kg/m}^3$), an estimate for the volume of insulation can be determined, where t_i is the thickness of the insulation and V_i and W_i are the volume and weight of the insulation respectively (Sinnott and Towler, 2020b):

$$V_i = \pi D_c H_v t_i = \pi \times 1.4 \times 6.5 \times 50 \times 10^{-3} = 1.43 \text{ m}^3 \quad (87)$$

$$W_i = V_i \rho_i g = 1.43 \times 130 \times 9.81 = 1.8 \text{ kN} \quad (88)$$

To account for fittings, sealing, and moisture absorption around the insulation, the weight of the insulation is doubled, giving a total insulation weight of 3.6 kN (Sinnott and Towler, 2020b). The total weight of the shell, plates and insulation can now be calculated:

$$W_{tot} = W_s + W_p + W_i = 27 + 39 + 3.6 = 70 \text{ kN} \quad (89)$$

5.2.4 Analysis of Stresses

5.2.4.1 Pressure Stress The longitudinal and circumferential stresses due to pressure are given by the following equations, where t_b is the wall thickness at the bottom of the vessel and σ_l and σ_h are the longitudinal and circumferential stresses respectively (Sinnott and Towler, 2020b).

$$\sigma_l = \frac{P_c D_c}{4t_b} = \frac{0.135 \times 1.4 \times 10^3}{4 \times 11} = 4.30 \text{ N/mm}^2 \quad (90)$$

$$\sigma_h = \frac{P_c D_c}{2t_b} = \frac{0.135 \times 1.4 \times 10^3}{2 \times 11} = 8.60 \text{ N/mm}^2 \quad (91)$$

5.2.4.2 Dead Weight Stress The stress due to the weight of the vessel, σ_w , can be calculated using Equation (92) (Sinnott and Towler, 2020b):

$$\sigma_w = \frac{W_{tot}}{\pi(D_c + t_b)t_b} = \frac{70 \times 10^3}{11\pi(1400 + 11)} = 1.44 \text{ N/mm}^2 \quad (92)$$

5.2.4.3 Bending Stress As the distillation column is small, the bending stress on the column will be negligible compared to the pressure and dead weight stress imparted on the column. Therefore, it can be neglected due to insufficient wind and seismic loads which will not cause a bending moment (Sinnott and Towler, 2020b).

The greatest difference between the major stresses on the column is equal to the difference in the circumferential stress calculated in Equation (91) and the resultant longitudinal stress (σ_z):

$$\sigma_z = \sigma_l - \sigma_w = 4.30 - 1.44 = 2.86 \text{ N/mm}^2 \quad (93)$$

$$\Delta\sigma_{max} = 8.60 - 2.86 = 5.74 \text{ N/mm}^2 \quad (94)$$

The maximum difference in stress is 5.74 N/mm^2 , which is far below the maximum allowable stress of 304 stainless steel (120 N/mm^2). Therefore, the thickness of the column walls at 7-11 mm is suitable for the column design.

5.3 Skirt Support Design

The skirt is designed to be able to withstand the pressure, dead weight and bending stresses exerted by the column. The skirt support will be made from carbon steel and is attached to the base of the column via welding (Sinnott and Towler, 2020b).

5.3.1 Maximum Dead Weight Load

The dead weight load occurs is at its maximum when the column is filled with water. This weight can be approximated using the following relation, where W_v is the total weight of the vessel calculated in Section (5.2.3.3):

$$W_{max} = \left(\frac{\pi}{4}D_c^2H_v\right)\rho g + W_{tot} = \left(\frac{\pi}{4} \times 1.4^2 \times 6.5\right)1000 \times 9.81 + 70 = 168.2 \text{ kN} \quad (95)$$

5.3.2 Wind Loading

For design, the wind pressure (P_w) can be taken as 1280 N/m^2 . The wind loading (F_w) on the column can be approximated by multiplying the wind pressure with the effective column diameter (D_{eff}).

$$D_{eff} = D_c + 2(t_b + t_i) = 1.4 + 2(11 + 50) \times 10^{-3} = 1.522 \text{ m} \quad (96)$$

$$F_w = P_w D_{eff} = 1280 \times 1.522 = 1950 \text{ N/m} \quad (97)$$

The maximum bending moment (M_s) at the bottom of the column can be calculated from the wind loading and the height of the column (Sinnott and Towler, 2020b):

$$M_s = \frac{F_w H_v^2}{2} = \frac{1950 \times 6.5^2}{2} = 42000 \text{ N} = 42 \text{ kN} \quad (98)$$

5.3.3 Skirt Thickness

The thickness of the skirt (t_{sk}) must be able to comfortably resist the dead weight and bending loads exerted on it by the column. As a first approximation, the skirt thickness will be assumed to be 15 mm. The bending stress in the skirt (σ_{bs}) can be calculated from the maximum bending moment found from Equation (98):

$$\sigma_{bs} = \frac{4M_s}{\pi(D_s + t_{sk})t_{sk}D_s} = \frac{4 \times 42 \times 10^3 \times 10^3}{\pi(1400 + 15) \times 1400 \times 15} = 1.8 \text{ N/mm}^2 \quad (99)$$

To calculate the maximum and operating dead weight stress in the skirt (σ_{ws}):

$$\sigma_{ws}(\text{maximum}) = \frac{W_{v,max}}{\pi(D_s + t_{sk})t_{sk}} = \frac{168.2 \times 10^3}{\pi(1400 + 15)15} = 2.52 \text{ N/mm}^2 \quad (100)$$

$$\sigma_{ws}(\text{operating}) = \frac{W_{v,op}}{\pi(D_s + t_{sk})t_{sk}} = \frac{70 \times 10^3}{\pi(1400 + 15)15} = 1.05 \text{ N/mm}^2 \quad (101)$$

Hence the maximum compressive and tensile resultant stresses on the skirt can be found via Equations (102) and (103) (Sinnott and Towler, 2020b):

$$\sigma_s(\text{tensile}) = \sigma_{bs} - \sigma_{ws}(\text{operating}) = 1.8 - 1.05 = 0.75 \text{ N/mm}^2 \quad (102)$$

$$\sigma_s(\text{compressive}) = \sigma_{bs} + \sigma_{ws}(\text{maximum}) = 1.8 + 2.52 = 4.32 \text{ N/mm}^2 \quad (103)$$

To ensure the skirt thickness is satisfactory, the following inequalities should be true such that at maximum wind and weight loading (Sinnott and Towler, 2020b):

$$\sigma_s(\text{tensile}) < S_s E \sin \theta_s \quad (104)$$

$$0.75 < 89 \times 1.0 \times \sin(90) = 89 \therefore \text{TRUE} \quad (105)$$

$$\sigma_s(\text{compressive}) < 0.125 E_Y \frac{t_{sk}}{D_s} \sin \theta_s \quad (106)$$

$$4.32 < 0.125 \times 200000 \times \frac{15}{4000} \times \sin 90 = 94 \therefore \text{TRUE} \quad (107)$$

Where S_s is the maximum allowable design stress for carbon steel (89 N/mm²), E is the weld joint efficiency (= 1.0), E_Y is the Young's modulus of the skirt material (200000 N/mm²) and θ_s is the base angle of the conical skirt (assumed 90°). The inequalities above are satisfied, therefore adding 2 mm of corrosion resistance to the walls gives a final skirt thickness of 17 mm.

6 Economics Evaluation

6.1 Total Capital Cost of Node 4

The MATLAB function `equipment_cost.m` was developed to determine the cost of the units in the node. The function uses the costing parameters defined in (Sinnott and Towler, 2020c), and returns a price for the purchased equipment cost (C_e), as well as a fixed capital cost estimate for the unit (C_{FC}). Table (10) shows the outputs from the MATLAB script and the total capital cost of Node 4:

Table 10: Summary of unit and capital costs for Node 4.

| Item | Material | C_e | Quantity | $\sum C_e$ | C_{FC} |
|---------------------|---------------------|---------------|----------|-----------------|------------------|
| Accumulator | Carbon steel | \$ 14,000 | 1 | \$ 14,000 | \$ 82,800 |
| Belt for Dryer | Carbon steel | \$ 83,200 | 1 | \$ 83,200 | \$ 83,200 |
| Centrifugal Pump | 304 stainless steel | \$9000-12,000 | 17 | \$178,000 | \$178,000 |
| Condenser | Carbon steel | \$120,000 | 1 | \$120,000 | \$720,000 |
| Distillation Column | 304 stainless steel | \$ 48,200 | 1 | \$ 48,200 | \$288,000 |
| Dryer | 304 stainless steel | \$117,000 | 1 | \$117,000 | \$266,000 |
| Ethanol Mixing Tank | 304 stainless steel | \$ 40,000 | 1 | \$ 40,000 | \$240,000 |
| Hammer Mill | Cast steel | \$ 28,200 | 1 | \$ 28,200 | \$128,000 |
| Heat Exchanger | Carbon steel. | \$ 30,000 | 1 | \$ 30,000 | \$180,000 |
| Precipitation Tank | 304 stainless steel | \$ 45,000 | 2 | \$ 90,000 | \$540,000 |
| Reboiler | Carbon steel | \$ 95,000 | 1 | \$ 95,000 | \$570,000 |
| Storage Tank | Carbon steel | \$ 14,000 | 2 | \$ 28,000 | \$120,000 |
| Valve Tray | 304 stainless steel | \$ 845 | 21 | \$ 17,700 | \$107,000 |
| Washing Tank | 304 stainless steel | \$ 40,000 | 2 | \$ 80,000 | \$480,000 |
| | | | | $\sum C_{FC} =$ | 3,900,000 |

Therefore, the expected capital cost of the plant (including cost of equipment, instrumentation, engineering, construction, contractor fees and contingency) is estimated to be \$4 million, with an accuracy of ± 30 per cent.

6.2 Fixed Operating Costs

It is assumed that Node 4 will require five workers per shift for operation. As each batch will take approximately eight hours, and three batches will be conducted each day, and so three shifts will be required for this type of operation. Workers will be paid a salary \$30,000 per annum, hence the total labour cost per annum can be determined:

$$\text{cost} = \text{workers} \times \text{no. shifts} \times \text{salary} = 5 \times 3 \times 30,000 = \$450,000/\text{annum} \quad (108)$$

6.3 Variable Operating Costs

As the orange peels are introduced into the pectin plant in Node 3, these will not be considered for economic analysis in Node 4.

6.3.1 Ethanol

As the distillation column D-401 has been designed to be able to recover 95 wt.% of the ethanol used in Node 4, only 223 kg of 96% (v/v) ethanol is required per batch. This equates to approximately 221 tonnes of ethanol required per annum. Assuming the price of ethanol is \$0.5/kg, the total cost of ethanol can be calculated per annum (Casas-Orozco et al., 2015):

$$\text{cost of ethanol} = 221 \times 10^3 \times 0.5 = \$110,000/\text{annum} \quad (109)$$

6.4 Pectin Sales

140 kg of pectin is produced per batch cycle, approximately 140 tonnes of pectin per annum. Pectin will be sold as a powdered solid, for the price of \$25/kg. This gives an estimated pectin revenue of:

$$\text{pectin income} = 140 \times 10^3 \times 25 = \$3,500,000/\text{annum} \quad (110)$$

6.5 Economic Summary

The total capital cost for Node 4 will surmount to \$4 million, with an accuracy of ± 30 per cent. The operating costs per annum will be \$450,000, and the cost of ethanol per annum is \$110,000. This gives a yearly profit of approximately \$2.9 million - this figure does not take into account energy requirements by the node, which is supplied from Node 5, nor the cost of the raw material (orange peel) in Node 3. A more detailed economic analysis will be detailed in Design Report B7, which will include total payback times and profit margins for the plant as a whole.

7 Summary

This report has focused on the detailed design of distillation column D-401, which is used for the recovery of ethanol in Node 4, where large quantities of ethanol would otherwise be wasted. The column permits the savings of approximately 3900 kg of ethanol per batch, which leads to savings of approximately 4000 tonnes of ethanol per annum. Taking the price of ethanol to be \$0.5/kg, this equates to a raw material cost saving of \$2 million dollars, which incentivises the operation of the column in the plant (Casas-Orozco et al., 2015).

It was calculated that the distillation column is required to be 1.4 m in diameter, 7.5 m in height, with a wall thickness of 11 mm. The distillation column and valve plates will be constructed from 304 stainless steel, and 21 valve plates are needed for the required ethanol separation. A skirt support was also designed for the column, which is required to be a height of one metre with a wall thickness of 17 mm. The column has also been modelled in the simulation software Pro/ii (see Section (4.9)), in which accurate simulated values for the physical system properties, energy requirements and column feasibility were obtained.

The economic analysis conducted in Section (6) showed the expected total capital cost of the Node to be US \$4 million with an accuracy of ± 30 per cent. The fixed operating costs, in which five workers are assumed to operate the node adds to \$450,000 per annum. The cost of raw materials (ethanol) and utilities for Node 4 are expected to be \$110,000 per annum, meaning the total operating cost of the plant will be \$560,000 per annum. Sales revenue from pectin will generate \$3.5 million per annum - this gives a profit per annum of approximately \$2.9 million for the node. However, this figure does not account energy requirements for the distillation column (which will be supplied by Node 5) nor the raw material costs from Node 3.

Before the commissioning of the plant, further research and development is essential to understand the optimum conditions and specifications for each unit in Node 4. The following statements are recommended for further research into Node 4:

- Pilot plant analysis of the node for greater understanding of optimum process conditions, batch times, batch sizing, and piping layout.
- In-depth analysis of each individual unit - detailed specification sheets, engineering drawings and mechanical designs for all processing units, pumps and valves in the node.
- In-depth analysis of control strategies used in the node, followed by a revised piping and instrumentation diagram.
- Revision of the economic analysis conducted to increase the accuracy of the estimated capital cost of the node.

A Auxiliary Equipment Specification

A.1 Centrifugal Pump Specification

Centrifugal pump CP-404 is required to pump 1350 kg/h of impure ethanol solution from storage tank T-402 to heat exchanger HEX-401 and distillation column D-401. Figure (13) shows a schematic of the pump location, fittings and approximate pipe lengths around the distillation column.

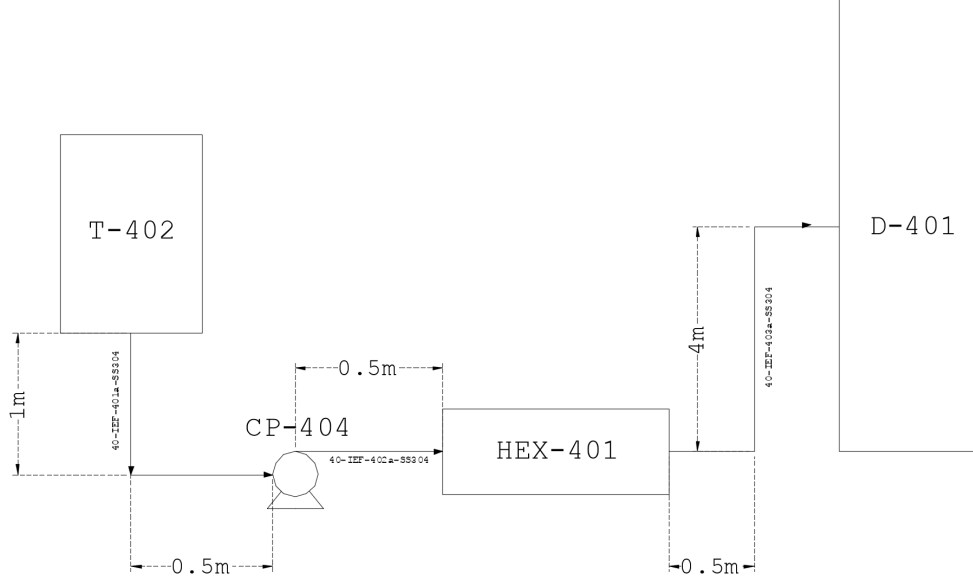


Figure 13: Schematic of pump with approximate pipe dimensions and fittings.

A.1.1 Dynamic Head Loss

The dynamic head loss in the system due to pressure drop can be determined from the Darcy-Weisbach equation (Chanson, 2004):

$$\Delta P = \frac{4\rho u^2 L}{D_i} \Phi \quad (111)$$

Where ρ is the fluid density (found in Section (4.9) to be 762 kg/m³), L is the pipe length, u is the fluid velocity through the pipe and D_i is the internal diameter of the pipe. The friction factor of the pipe, Φ , can be calculated using the Blasius (Lampinen et al., 2001):

$$\Phi = \frac{0.316}{Re^{0.25}} \quad (112)$$

It is assumed that the fluid velocity of the pipe will be 0.5 m/s, hence the pressure drop can be determined using the relationship between flowrate, velocity and Equation (111).

Table 11: Pressure drop calculations for each pipe.

| Pipe Number | D_i (mm) | L (m) | Re | Φ | u (m/s) | ΔP (Pa) |
|-------------------|------------|---------|-------|--------|-----------|-----------------|
| 40-IEF-401a-SS304 | 40 | 1.5 | 15200 | 0.0284 | 0.5 | 813 |
| 40-IEF-402a-SS304 | 40 | 0.5 | 15200 | 0.0284 | 0.5 | 271 |
| 40-IEF-403a-SS304 | 40 | 4.5 | 15200 | 0.0284 | 0.5 | 2438 |
| | | | | | | $\Sigma = 3500$ |

The pressure drop due to fittings on the pipe must also be considered. Using K-value friction data from (Bai and Bai, 2019), the pressure drop can be determined from fittings:

Table 12: Pressure drop calculations for pipe fittings.

| Pipe Number | Fitting | K | ΔP (Pa) |
|-------------------|--------------------------|-----|-----------------|
| 40-IEF-401a-SS304 | Long radius elbow, 90° | 0.6 | 5.83 |
| | Gate valve, full open | 0.2 | 1.94 |
| 40-IEF-402a-SS304 | Gate valve, full open x2 | 0.2 | 3.88 |
| 40-IEF-403a-SS304 | Long radius elbow, 90° | 0.6 | 5.83 |
| | Gate valve, full open | 0.2 | 1.94 |
| | | | $\Sigma = 19.4$ |

The total dynamic pressure drop can be considered as a pressure head, from the summation of the total values calculated in Table (11) and Table (12):

$$\text{dynamic head loss} = \frac{3500 + 19.4}{762 \times 9.81} = 0.47 \text{ m} \quad (113)$$

A.1.2 Static Head Loss

The static head loss due to differences in elevation can be determined from Figure (13). As both units are at atmospheric pressure, the static head loss is equivalent to only the difference in height.

$$\text{static head loss} = \Delta z = 4 - 1 = 3 \text{ m} \quad (114)$$

A.1.3 Overall Head Loss and Power Consumption

The overall head loss can be calculated by the summation of head losses in Equations (113) and (114):

$$\text{overall head loss} = \text{dynamic head loss} + \text{static head loss} = 0.47 + 3 = 3.47 \text{ m} \quad (115)$$

The typical efficiency of a centrifugal pump is 70 per cent (Neutrium, 2012). To calculate the hydraulic power of the pump, Equation (117) is used:

$$P_h = \frac{Q\rho gh_o}{3.6 \times 10^6} = \frac{1.77 \times 762 \times 9.81 \times 3.3}{3.6 \times 10^6} = 12.8 \text{ W} \quad (116)$$

Where P_h is the hydraulic power and h_o is the overall head loss. The shaft power (P_s) is the sum of the hydraulic power and power losses due to inefficiency (η):

$$P_s = \frac{P_h}{\eta} = \frac{12.8}{0.7} = 18 \text{ W} \quad (117)$$

A.1.4 Pump Selection

The recommended pump for CP-404 has been selected from (Calpeda, 2020). The NR4-50 in-line centrifugal pump is recommended due to its reliability when operating at low flowrates and its compact design. Figure (14) shows the system curve and pump curve plotted for pump NR4-50, with data taken from (Calpeda, 2020).

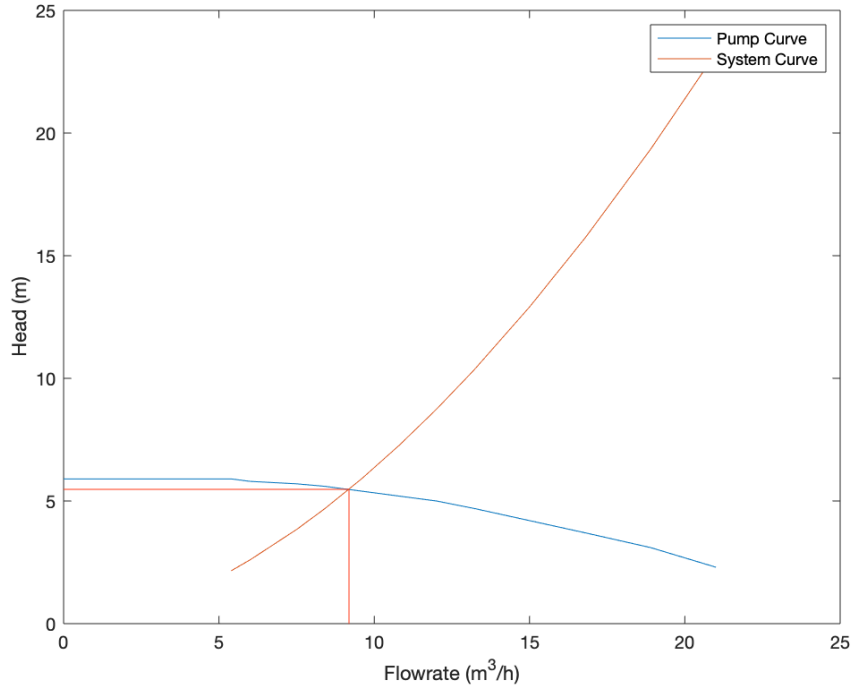


Figure 14: Pump performance curve for NR4-50 and system curve.

The operating point occurs at the flowrate where the two curves intersect. For this pump, this is at a flowrate of approximately 9 m³/h and a head of 6 metres.

A.1.5 Net Positive Suction Head

Vapour bubbles that burst due to areas of low pressure in the pump can cause significant damage to the impeller and pump casing. The Net Positive Suction Head (NPSH) is a measure of how close the fluid is to cavitation. To avoid cavitation, the $NPSH_{\text{available}}$ should be above the required NPSH. The required NPSH for pump NR4-50 should be at least above 2 metres to avoid cavitation (Calpeda, 2020).

$$NPSH_{\text{available}} = \frac{P_I}{\rho g} + H_s - \frac{P_p}{\rho g} - \frac{P_v}{\rho g} \quad (118)$$

$$NPSH_{\text{available}} = \frac{101,325}{762 \times 9.81} + 0.5 - \frac{3500}{762 \times 9.81} - \frac{5950}{762 \times 9.81} = 12.8 \text{ m} \quad (119)$$

The available NPSH is much larger than the required NPSH, therefore the risk of cavitation at the operating flowrate is small, and pump NR4-50 is suitable for use.

A.1.6 Pump Specification Sheet

Table 13: CP-404 specification sheet.

| Pump Type | Centrifugal | Item Tag | CP-404 |
|------------------------------|-------------|-------------------------------|---------|
| Capacity (m ³ /h) | 9 | NPSH _{available} (m) | 12.8 |
| Head Provided (m) | 6 | NPSH _{required} (m) | 2 |
| Efficiency | 65% | Manufacturer | Calpeda |
| Shaft Power (W) | 18 | Pump Model | NR4-50 |

A.2 Control Valve Specification

Globe control valve (CV-402c) is used to change the flowrate of material entering distillation column D-401 via reflux. This valve requires accurate control over a range of flowrates as the flow of reflux is used to control the temperature at the top of the column - if the top temperature is incorrect whilst the column is in operation, the product produced will be off specification. The GV2 pneumatic control valve by (Ecoflo, 2019) is suitable for the regulation of temperature and flowrate, therefore this valve is applicable for use in the reflux application. The specification sheet for valve GV2 is given in Section (A.2.1).

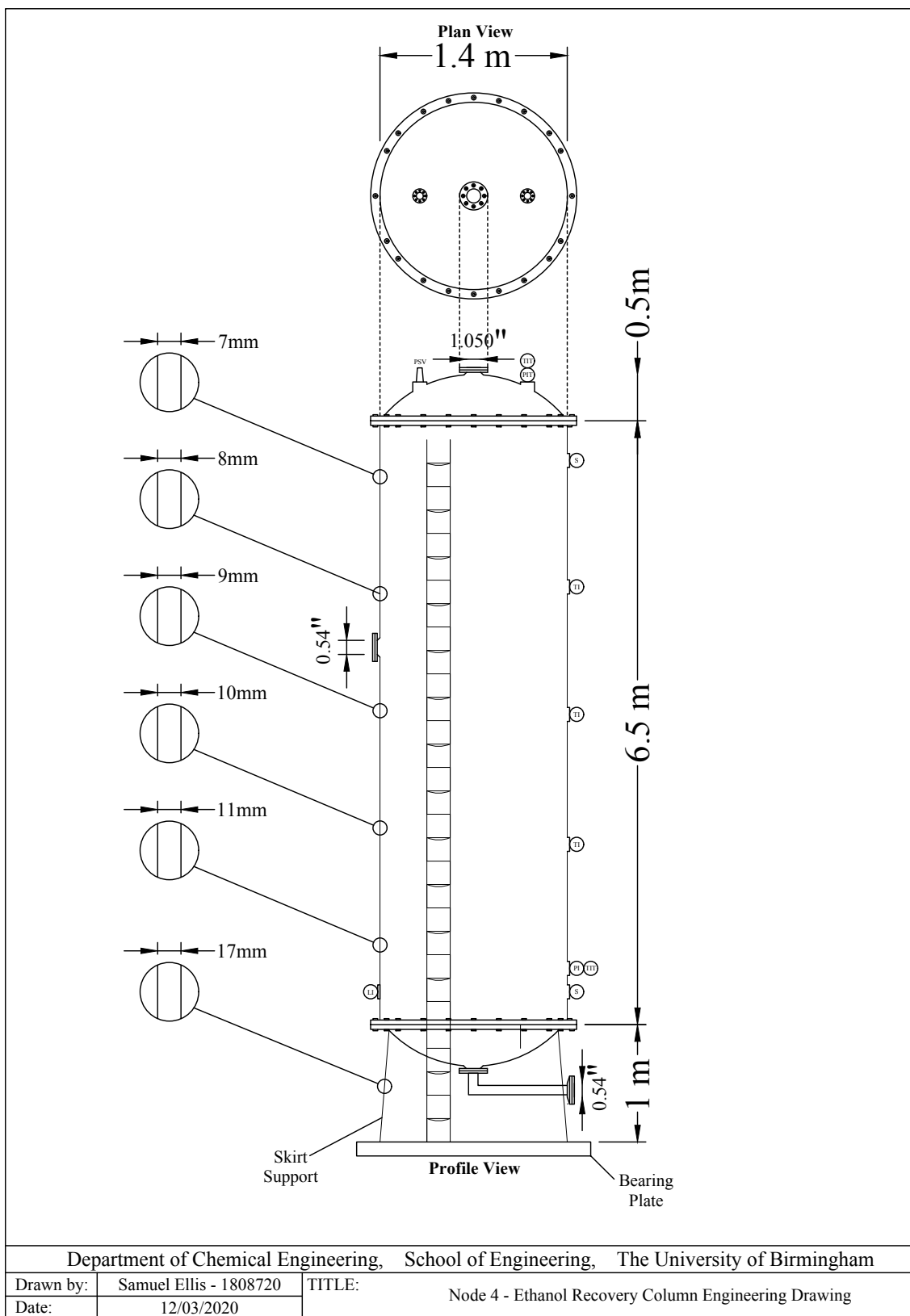
A.2.1 Valve Specification Sheet

Table 14: CV-402c specification sheet.

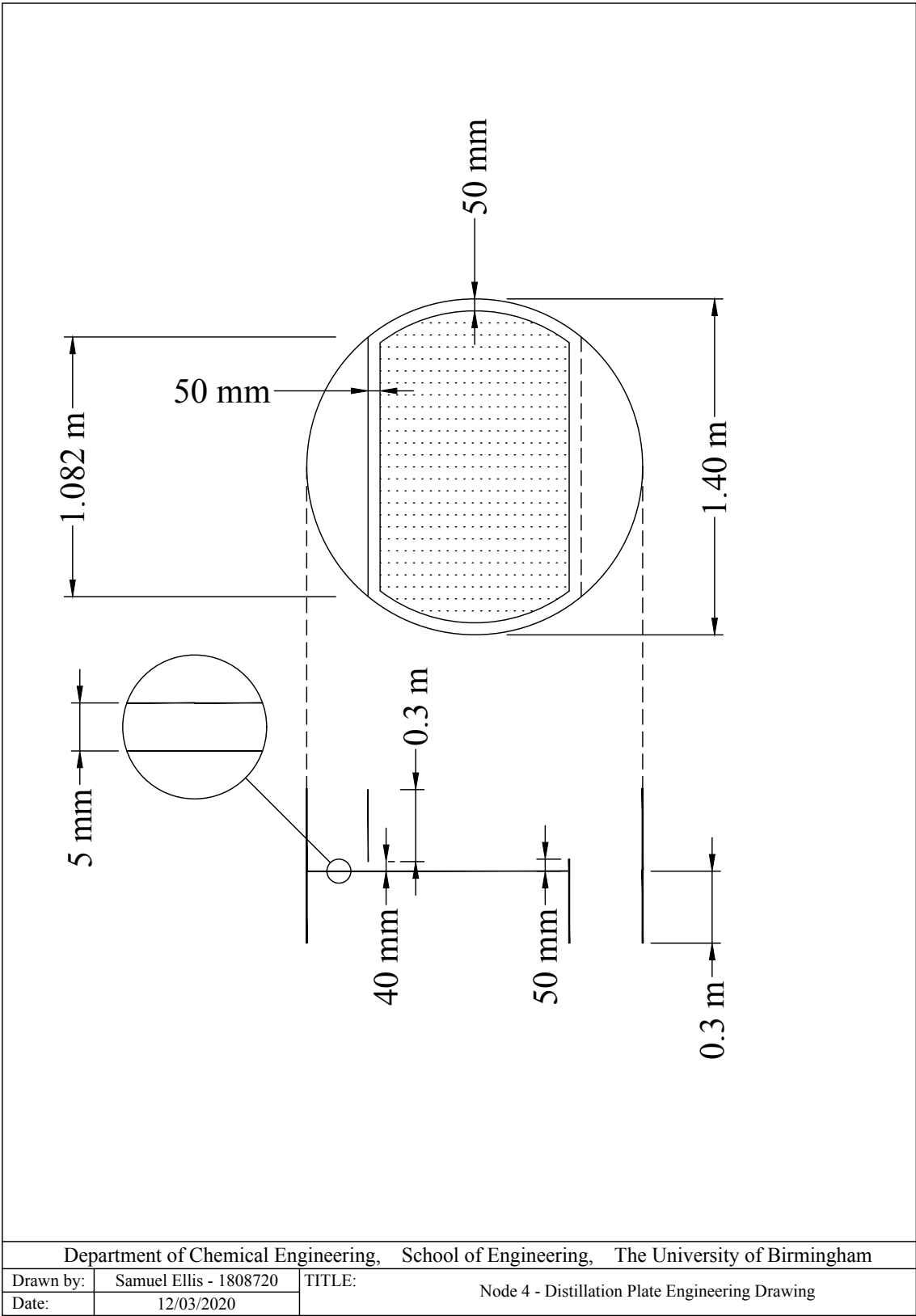
| Valve Type | Globe | Item Tag | CV-402c |
|---------------------------|---------------|------------------|-----------|
| Fluid | Ethanol-Water | Actuation Method | Pneumatic |
| Material | AISI 304 | Fail Position | Closed |
| Operating Temperature (K) | 323 | Manufacturer | Ecoflo |
| Pressure Drop (kPa) | 5.2 | Valve Model | GV2 |

B Mechanical Design

B.1 Distillation Column D-401



B.2 Valve Plate



C Specification Sheets

C.1 Equipment List

Table 15: Node 4 equipment list.

| Item | ID Tag | Quantity |
|-------------------------------|------------|----------|
| Batch Conveyor Dryer | DY-401 | 1 |
| Centrifugal Pump | CP | 18 |
| Distillation Column | D-401 | 1 |
| Hammer Mill | G-401 | 1 |
| Heat Exchanger | HEX-401 | 1 |
| Mixing Tank | MT-401 | 1 |
| Precipitation Tank | PT-401/402 | 2 |
| Buffer Tank | T-401 | 1 |
| Impure Ethanol Storage Vessel | T-402 | 1 |
| Pure Ethanol Storage Vessel | T-403 | 1 |
| Valve Plates | VP-401 | 21 |
| Washing Tank | WT-401/402 | 2 |

C.2 Batch Conveyor Dryer

| | | | |
|--------------------------------|---|--------------------|----------------------|
| DP3 Specification Sheet | | Written By: | Samuel Ellis |
| Plant: | Pectin Production | Item: | Batch Conveyor Dryer |
| Node: | 4 – Pectin Purification and Ethanol Recovery | ID Tag: | DY-401 |
| Location and Purpose: | The pectin gel is dried using warm air in a batch dryer before it is milled into a fine powder product. | | |
| 1. Operation | mode | continuous | |
| | operating cycle | 1.5 | h |
| 2. Feed | (a) material to be dried | pectin | |
| | (b) feed rate | 97 | kg/h |
| | (c) nature of feed | slurry | |
| | (d) physical properties of solids | | |
| | initial moisture content | 0.33 | kg liq/kg |
| | heat capacity | 2.16 | kJ/kg°C |
| | bulk density, wet | 680 | kg/m ³ |
| | (e) moisture to be removed | | |
| | chemical composition | 0.75 | wt.% eth |
| | | 0.25 | wt.% wat |
| | boiling point at 1 bar | 78.2 | °C |
| | heat of vaporisation | 0.85 | MJ/kg |
| | heat capacity | 2.43 | kJ/kg°C |
| 3. Product | (a) final moisture content | 0.05 | kg liq/kg |
| | (b) physical characteristics | fibrous | |
| 4. Design Restraints | (a) maximum temperature when wet | 80 | °C |
| | when dry | 60 | °C |
| | (b) manner of degradation | thermal | |
| | (c) space limitations | - | |

| | | | |
|---|---|--------------------|----------------------|
| DP3 Specification Sheet | | Written By: | Samuel Ellis |
| Plant: | Pectin Production | Item: | Conveyor Batch Dryer |
| Node: | 4 – Pectin Purification and Ethanol Recovery | ID Tag: | DY-401 |
| 5. Utilities | (a) air available at | | |
| | maximum quantity | - | kg/h |
| | cost | 0 | \$/kg |
| 6. Recommended Materials of Construction | (a) parts in contact with wet material | SS-304 | |
| | (b) parts in contact with vapour | SS-304 | |

| | | | |
|--------------------------------|--|--------------------|-------------------------|
| DP3 Specification Sheet | | Written By: | Samuel Ellis |
| Plant: | Pectin Production | Item: | Belt for Conveyor Dryer |
| Node: | 4 – Pectin Purification and Ethanol Recovery | ID Tag: | Belt for DY-401 |
| Location and Purpose: | - | | |
| 1. Operation | mode | continuous | |
| | incline | 0° | |
| | power required | 0.023 | HP |
| 2. Sizing | (a) belt type | flat | |
| | (b) belt length | 90 | ft |
| | (c) belt width | 5 | ft |
| 3. Chute | (a) chute design | circular | |
| | (b) chute angle | 35° | |

C.3 Distillation Column and Valve Plate

| | | | |
|---------------------------------------|--|--------------------|---------------------|
| <i>DP3 Specification Sheet</i> | | Written By: | Samuel Ellis |
| Plant: | Pectin Production | Item: | Distillation Column |
| Node: | 4 – Pectin Purification and Ethanol Recovery | ID Tag: | D-401 |
| 1. Operation | mode | continuous | |
| | conditions | 353 | K |
| | | 101 | kPa |
| 2. Flow | (a) feed - temperature | 350 | K |
| | pressure | 1 | bar |
| | viscosity | 0.447 | cP |
| | density (liquid) | 762 | kg/m ³ |
| | (b) bottoms - temperature | 372 | K |
| | pressure | 1 | bar |
| | viscosity | 0.447 | cP |
| | density (liquid) | 955 | kg/m ³ |
| | (c) overhead - temperature | 360 | K |
| | pressure | 1.43 | bar |
| | viscosity | 0.447 | cP |
| | density (liquid) | 736 | kg/m ³ |
| 3. Dimensions | (a) column - height | 7.50 | m |
| | - inside diameter | 1.40 | m |
| | - shell/wall thickness | 11 | mm |
| | (b) trays - number of trays | 21 | - |
| | - type | valve | - |
| | - spacing | 0.3 | m |
| | (c) support - type | skirt | - |
| | - height | 1.0 | m |
| | (d) insulation - thickness | 50 | mm |

| | | | |
|------------------------------------|-----------------------|---------------------|-----|
| 4. Material of Construction | (a) shell | 304 stainless steel | |
| | (b) trays | 304 stainless steel | |
| | (c) support | carbon steel | |
| | (d) insulation | mineral wool | |
| 5. Operating Data | (a) ΔP column | 0.206 | bar |
| | (b) % flooding | 71 | |

| | | | | |
|---------------------------------------|--|---------------------|--------------|--|
| <i>DP3 Specification Sheet</i> | | Written By: | Samuel Ellis | |
| Plant: | Pectin Production | Item: | Valve Plate | |
| Node: | 4 – Pectin Purification and Ethanol Recovery | ID Tag: | VP-401 | |
| 1. Dimensions | (a) plate inside diameter | 1.40 | m | |
| | (b) hole size | 5 | mm | |
| | (c) hole pitch | 13 | mm | |
| | (d) total holes | 4000 | | |
| | (e) active holes | 4000 | | |
| | (f) turn-down | 70% of max rate | | |
| | (g) plate spacing | 0.3 | m | |
| | (f) plate thickness | 0.5 | mm | |
| | (h) unperforated edge strip width | 50 | mm | |
| | (i) calming zone width | 50 | mm | |
| | (j) plate pressure drop | 106 | mm liq | |
| 2. Material of Construction | (a) plate material | 304 stainless steel | | |
| | (b) downcomer material | mild steel | | |

C.4 Hammer Mill

| | | | |
|---|--|--------------------|--------------|
| <i>DP3 Specification Sheet</i> | | Written By: | Samuel Ellis |
| Plant: | Pectin Production | Item: | Hammer Mill |
| Node: | 4 – Pectin Purification and Ethanol Recovery | ID Tag: | G-401 |
| Location and Purpose: | After drying the pectin gel in DY-401, the coagulated pectin is ground into a fine powder ready for dispersion in the jam solution and sale. | | |
| 1. Model Name | 00 Hinged Hammer Pulveriser (Sturtevant Mill Co., Boston, MA) | | |
| 2. Operation | (a) mode | batch | |
| | (b) conditions | 313 | K |
| | | 101 | kPa |
| 3. Feed | (a) material to be milled | pectin | |
| | (b) feed rate | 145 | kg/batch |
| | (c) nature of feed | fibrous solid | |
| 4. Mill Characteristics | (a) length | 29 | in. |
| | (b) width | 36 | in. |
| | (c) inner dimensions | | |
| | diameter | 16 | in. |
| | width | 11 | in. |
| | (d) feed opening | 12x12 | in. |
| | (e) pulley speed | 1520 | rpm |
| 5. Recommended Materials of Construction | (a) main body | SS-304 | |
| | (b) hammers | hardened steel | |

C.5 Heat Exchanger

| | | | |
|---------------------------------------|---|--------------------|-------------------|
| <i>DP3 Specification Sheet</i> | | Written By: | Samuel Ellis |
| Plant: | Pectin Production | Item: | Heat Exchanger |
| Node: | 4 – Pectin Purification and Ethanol Recovery | ID Tag: | HEX-401 |
| Location and Purpose: | This heat exchanger is located just before distillation column D-401 and acts as a pre-heater before the impure ethanol solution enters the column. | | |
| 1. Operation | mode | continuous | |
| | type | shell and tube | |
| | power required | 0.023 | HP |
| 2. Feed | (a) flow | 470 | kg/h |
| | (b) physical properties of solution | | |
| | heat capacity | 2.51 | kJ/kg°C |
| | bulk density | 854 | kg/m ³ |
| | liquid viscosity | 28.2 | cP |
| 3. Operating Conditions | (a) inlet temperature | | |
| | tube side | 25 | °C |
| | shell side (steam) | 170 | °C |
| | (b) outlet temperature | | |
| | tube side | 70 | °C |
| | shell side (steam) | 122 | °C |
| | (c) operating pressure | 101 | kPa |
| | steam pressure | 6 | bar |

C.6 Mixing Tank

| | | | | |
|--------------------------------|--|--------------------|--------------------------|--|
| DP3 Specification Sheet | | Written By: | Samuel Ellis | |
| Plant: | Pectin Production | Item: | Pure Ethanol Mixing Tank | |
| Node: | 4 – Pectin Purification and Ethanol Recovery | ID Tag: | MT-401 | |
| Location and Purpose: | The distilled ethanol solution from D-201 is recycled using a top up stream of 96% (v/v) ethanol. These streams are mixed together for the desired concentration of 86% (v/v) ethanol. | | | |
| 1. Operation | mode | continuous | | |
| | conditions | 313 | K | |
| | | 101 | kPa | |
| | mixing time | - | h | |
| | mixing type | liquid-liquid | | |
| | solids content | - | | |
| 2. Feed | (a) flow | 402 | kg/batch | |
| | (b) agitated solution | water | | |
| | | ethanol | | |
| | (c) physical properties of solution | | | |
| | heat capacity | 2.17 | kJ/kg°C | |
| | bulk density | 818 | kg/m ³ | |
| | liquid viscosity | 1.1 | cP | |
| 3. Tank Characteristics | (a) tank volume | 0.66 | m ³ | |
| | (b) tank diameter | 0.9 | m | |
| | (c) tank height (excluding conical heads) | 0.9 | m | |
| | (d) conical head height | 0.174 | m | |
| | (e) depth of liquid | | | |
| | maximum | 0.85 | m | |
| | normal | 0.78 | m | |
| | minimum | 0.62 | m | |

| | | | | |
|---|--|--------------------|--------------------------|--|
| DP3 Specification Sheet | | Written By: | Samuel Ellis | |
| Plant: | Pectin Production | Item: | Pure Ethanol Mixing Tank | |
| Node: | 4 – Pectin Purification and Ethanol Recovery | ID Tag: | MT-401 | |
| 3. Tank Characteristics | (f) baffles | | | |
| | number of baffles | 4 | | |
| | baffle width | 0.075 | m | |
| 4. Impeller Characteristics | (a) impeller type | Rushton turbine | | |
| | number of impellers | 1 | | |
| | number of blades | disk | | |
| | impeller angle | - | | |
| | (b) impeller diameter | 0.45 | m | |
| | aperture diameter to remove impeller | 0.495 | m | |
| | (c) impeller speed | 37 | rpm | |
| 5. Recommended Materials of Construction | (a) mixing tank | SS-301 | | |
| | (b) impeller | SS-301 | | |
| | | | | |

C.7 Precipitation Tank

| | | | | |
|--------------------------------|---|--------------------|--------------------|--|
| DP3 Specification Sheet | | Written By: | Samuel Ellis | |
| Plant: | Pectin Production | Item: | Precipitation Tank | |
| Node: | 4 – Pectin Purification and Ethanol Recovery | ID Tag: | PT-401/402 | |
| Location and Purpose: | The pectin feed is mixed with ethanol in this tank. Pectin is insoluble in ethanol upon mixing, and so it precipitates out as a gel like substance. | | | |
| 1. Operation | mode | batch | | |
| | conditions | 313 | K | |
| | | 101 | kPa | |
| | mixing time | 2 | h | |
| | mixing type | liquid-liquid | | |
| | solids content | negligible | | |
| 2. Feed | (a) flow | 1983 | kg/batch | |
| | (b) agitated solution | water | | |
| | | ethanol | | |
| | | pectin | | |
| | | hydrochloric acid | | |
| | | soluble sugars | | |
| | (c) physical properties of solution | | | |
| | heat capacity | 2.51 | kJ/kg°C | |
| | bulk density | 854 | kg/m ³ | |
| | liquid viscosity | 28.2 | cP | |
| 3. Tank Characteristics | (a) tank volume | 3.16 | m ³ | |
| | (b) tank diameter | 1.6 | m | |
| | (c) tank height (excluding conical heads) | 1.6 | m | |
| | (d) conical head height | 0.310 | m | |

| | | | |
|---|--|------------------------------------|--------------------|
| <i>DP3 Specification Sheet</i> | | Written By: | Samuel Ellis |
| Plant: | Pectin Production | Item: | Precipitation Tank |
| Node: | 4 – Pectin Purification and Ethanol Recovery | ID Tag: | PT-401/402 |
| 3. Tank Characteristics | (e) depth of liquid | | |
| | maximum | 1.42 | m |
| | normal | 1.18 | m |
| | minimum | 0.94 | m |
| | (f) baffles | | |
| | number of baffles | 4 | |
| | baffle width | 0.133 | m |
| 4. Impeller Characteristics | (a) impeller type | pitched blade turbine | |
| | number of impellers | 1 | |
| | number of blades | 6 | |
| | impeller angle | 45° | |
| | (b) impeller diameter | 0.8 | m |
| | aperture diameter to remove impeller | 0.88 | m |
| | (c) impeller speed | 45 | rpm |
| 5. Cooling Coil Characteristics | (a) outside diameter | 0.053 | m |
| | (b) coil spacing (centre to centre) | 0.11 | m |
| | (c) number of coils | 15 | |
| 6. Recommended Materials of Construction | (a) mixing tank | SS-301 with interior rubber lining | |
| | (b) impeller | SS-301 | |
| | (c) cooling coils | SS-301 | |

C.8 Storage Vessels

C.8.1 Buffer Tank

| | | | |
|---------------------------------------|--|--------------------|-------------------|
| <i>DP3 Specification Sheet</i> | | Written By: | Samuel Ellis |
| Plant: | Pectin Production | Item: | Buffer Tank |
| Node: | 4 – Pectin Purification and Ethanol Recovery | ID Tag: | T-401 |
| Location and Purpose: | This storage tank will be used as a buffer tank for the pectin solution after evaporation. | | |
| 1. Operation | (a) feed | 88 | kg/h |
| | (b) stored solution | water | |
| | | ethanol | |
| | | pectin | |
| | | hydrochloric acid | |
| | | soluble sugars | |
| | (c) volumetric throughput | 0.1 | m ³ /h |
| | heat capacity | 2.51 | kJ/kg°C |
| | bulk density | 854 | kg/m ³ |
| | liquid viscosity | 28.2 | cP |
| 2. Sizing | (a) tank capacity | 4 | m ³ |

C.8.2 Impure Ethanol Storage Vessel

| | | | |
|---------------------------------------|---|--------------------|-------------------|
| <i>DP3 Specification Sheet</i> | | Written By: | Samuel Ellis |
| Plant: | Pectin Production | Item: | Buffer Tank |
| Node: | 4 – Pectin Purification and Ethanol Recovery | ID Tag: | T-403 |
| Location and Purpose: | This storage tank will be used as a buffer tank for the recovered ethanol, ready for use in the precipitation and washing stages. | | |
| 1. Operation | (a) feed | 391 | kg/h |
| | (b) stored solution | water | |
| | | ethanol | |
| | (c) volumetric throughput | 0.5 | m ³ /h |
| | heat capacity | 2.17 | kJ/kg°C |
| | bulk density | 818 | kg/m ³ |
| | liquid viscosity | 1.1 | cP |
| 2. Sizing | (a) tank capacity | 8 | m ³ |

C.8.3 Pure Ethanol Storage Vessel

| | | | |
|---------------------------------------|---|--------------------|-------------------|
| <i>DP3 Specification Sheet</i> | | Written By: | Samuel Ellis |
| Plant: | Pectin Production | Item: | Buffer Tank |
| Node: | 4 – Pectin Purification and Ethanol Recovery | ID Tag: | T-403 |
| Location and Purpose: | This storage tank will be used as a buffer tank for the recovered ethanol, ready for use in the precipitation and washing stages. | | |
| 1. Operation | (a) feed | 391 | kg/h |
| | (b) stored solution | water | |
| | | ethanol | |
| | (c) volumetric throughput | 0.5 | m ³ /h |
| | heat capacity | 2.17 | kJ/kg°C |
| | bulk density | 818 | kg/m ³ |
| | liquid viscosity | 1.1 | cP |
| 2. Sizing | (a) tank capacity | 8 | m ³ |

C.9 Washing Tank

| | | | | |
|--------------------------------|---|--------------------|-------------------|--|
| DP3 Specification Sheet | | Written By: | Samuel Ellis | |
| Plant: | Pectin Production | Item: | Washing Tank | |
| Node: | 4 – Pectin Purification and Ethanol Recovery | ID Tag: | WT-401/402 | |
| Location and Purpose: | The pectin precipitated in PT-401/402 is washed with ethanol in this tank. The pectin gel is unstable at pH<4, so it is washed with ethanol to remove acid impurities and soluble components. | | | |
| 1. Operation | mode | batch | | |
| | conditions | 298 | K | |
| | | 101 | kPa | |
| | mixing time | 0.5 | h | |
| | mixing type | liquid-liquid | | |
| | solids content | negligible | | |
| 2. Feed | (a) flow | 2276 | kg/batch | |
| | (b) agitated solution | water | | |
| | | ethanol | | |
| | | pectin | | |
| | | hydrochloric acid | | |
| | | soluble sugars | | |
| | (c) physical properties of solution | | | |
| | heat capacity | 2.19 | kJ/kg°C | |
| | bulk density | 809 | kg/m ³ | |
| | liquid viscosity | 107 | cP | |
| 3. Tank Characteristics | (a) tank volume | 8.64 | m ³ | |
| | (b) tank diameter | 2.2 | m | |
| | (c) tank height (excluding conical heads) | 2.2 | m | |
| | (d) conical head height | 0.43 | m | |

| | | | |
|---|--|-----------------------|--------------|
| DP3 Specification Sheet | | Written By: | Samuel Ellis |
| Plant: | Pectin Production | Item: | Washing Tank |
| Node: | 4 – Pectin Purification and Ethanol Recovery | ID Tag: | WT-401/402 |
| 3. Tank Characteristics | (e) depth of liquid | | |
| | maximum | 0.88 | m |
| | normal | 0.73 | m |
| | minimum | 0.59 | m |
| | (f) baffles | | |
| | number of baffles | 4 | |
| | baffle width | 0.185 | m |
| 4. Impeller Characteristics | (a) impeller type | pitched blade turbine | |
| | number of impellers | 1 | |
| | number of blades | 6 | |
| | impeller angle | 45° | |
| | (b) impeller diameter | 1.1 | m |
| | aperture diameter to remove impeller | 1.2 | m |
| | (c) impeller speed | 56 | rpm |
| 5. Cooling Coil Characteristics | (a) outside diameter | 0.074 | m |
| | (b) coil spacing (centre to centre) | 0.148 | m |
| | (c) number of coils | 15 | |
| 6. Recommended Materials of Construction | (a) mixing tank | SS-301 | |
| | (b) impeller | SS-301 | |
| | (c) cooling coils | SS-301 | |

D Distillation Apparatus Costing

The distillation column was costed using the `equipment_cost.m` function, using predetermined design data as the function input. The distillation column apparatus (including the condenser, reboiler and accumulator) was costed using a combination of a vertical pressure vessel, valve trays, a U-tube kettle reboiler, a U-tube heat exchanger and a storage tank. The pricing parameters given in Table (16) are taken from (Sinnott and Towler, 2020c) Chapter 6 and are used in the below calculations to determine the cost of each unit:

Table 16: Cost constants to determine the purchased equipment cost ($C_e = a + bS^n$).

| Unit | a | b | n |
|----------------------------------|-------|------|------|
| Vertical Pressure Vessel, 304 ss | 15000 | 68 | 0.85 |
| Valve Trays | 180 | 340 | 1.9 |
| U-Tube Kettle Reboiler | 25000 | 340 | 0.9 |
| Double Pipe Heat Exchanger | 1600 | 2100 | 1 |
| Storage Tank (Conical Head) | 5000 | 1400 | 0.7 |

To calculate the cost of the pressure vessel, the shell mass is required. The shell mass (m_{shell}) is a function of the column diameter (D_c), column length (L_c), the density of the material of construction (304 stainless steel = 8000 kg/m³), and the wall thickness of the column (t_w). The wall thickness is calculated using Equation (120):

$$t_w = \frac{P_c D_c}{2SE - 1.2P_c} \quad (120)$$

Where P_c is the design pressure of the column (Pa), S is the maximum allowable stress (Pa) and E is the welded joint efficiency. The column will be constructed from 304 stainless steel. The maximum allowable stress of 304 stainless steel at 80°C is approximately 1.2E+08 Pa (Sinnott and Towler, 2020a). Assuming the welds will be fully radiographed the welded joint efficiency can be neglected. The design pressure of the column is set to 10 per cent above the operating pressure of the column, hence the design pressure of the column is 101,325/0.9 \approx 113,000 Pa. With these assumptions, the wall thickness can be determined:

$$t_w = \frac{113000 \cdot 1.07}{2 \cdot 1.2E+08 \cdot 1.0 - 1.2 \cdot 113000} = 0.0005\text{m} \equiv 0.5\text{mm} \quad (121)$$

The wall thickness determined is lower than the minimum wall thickness (excluding corrosion allowance) of 1.5 mm defined in the ASME BPV Code Sec. VIII D.1 (Sinnott and Towler, 2020c). Therefore the selected wall thickness of the column will be 5 mm to also accommodate corrosion resistance. The shell mass can now be calculated:

$$m_{shell} = \pi D_c L_c t_w \rho = \pi \cdot 1.07 \cdot 8.4 \cdot 5E-03 \cdot 8000 = 1130\text{kg} \quad (122)$$

From the shell mass, a preliminary cost for the pressure vessel can be calculated using the data shown in Table (16):

$$C_e = 15000 + 68 \cdot 1130^{0.85} \approx 42,000 \text{ dollars in 2007} \equiv \$ 48,200 \text{ in 2020} \quad (123)$$

This can be converted to the cost of the unit in 2020 using cost escalation parameters defined in the `equipment_cost.m` function. The number of valve plates or stages (N) in the distillation

column has been determined to be 22 stages (including the reboiler), and as the column diameter is known, the cost of the valve trays can be determined:

$$C_e = 180 + 340 \cdot 1.07^{0.85} \cdot 21 \approx 11,400 \text{ dollars in 2007} \equiv \$ 13,000 \text{ in 2020} \quad (124)$$

As the trays will be constructed from 304 stainless steel, the cost of the trays is multiplied by a material factor of 1.3 found in (Sinnott and Towler, 2020c), making the summative cost of the trays equal to \$17,000. This costing process has been repeated for all major units and pumps in the node, and the final equipment costs are shown in Table (10).

E Final Mass and Energy Balance

| Stream | 4-01 | 4-02a | 4-02b | 4-03a | 4-03b | 4-04a | 4-04b | 4-05a | 4-05b | 4-06 |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Description | FROM NODE 3 | PEC TO PT-401 | PEC TO PT-402 | ETH TO PT-401 | ETH TO PT-402 | ETH OUT PT-401 | ETH OUT PT-402 | PEC OUT PT-401 | PEC OUT PT-402 | PEC TO WT-401 |
| Temperature (K) | 298 | 298 | 298 | 298 | 298 | 298 | 298 | 313 | 313 | 313 |
| Pressure (kPa) | 101 | 101 | 101 | 101 | 101 | 101 | 101 | 101 | 101 | 101 |
| Quantity | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) |
| Water | 196 | 196 | 196 | 237 | 237 | 378 | 378 | 54.8 | 54.8 | 54.8 |
| Pectin | 139 | 139 | 139 | - | - | - | - | 138 | 138 | 138 |
| HCl | - | - | - | - | - | - | - | - | - | - |
| Ethanol | - | - | - | 1062 | 1062 | 927 | 927 | 134 | 134 | 134 |
| Other | 362 | 362 | 362 | - | - | 344 | 344 | 18.1 | 18.1 | 18.1 |
| Air | - | - | - | - | - | - | - | - | - | - |
| Total | 697 | 697 | 697 | 1299 | 1299 | 1649 | 1649 | 345 | 345 | 345 |

| Stream | 4-07 | 4-08 | 4-09 | 4-10 | 4-11 | 4-12 | 4-13 | 4-14 | 4-15 | 4-16 |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Description | ETH TO WT-401 | ETH OUT WT-401 | PEC TO WT-402 | ETH TO WT-402 | ETH OUT WT-402 | PEC TO MP-401 | ETH OUT MP-401 | PEC TO DY-201 | HOT AIR DY-201 | AIR OUT DY-201 |
| Temperature (K) | 298 | 298 | 298 | 298 | 298 | 298 | 298 | 298 | 338 | 298 |
| Pressure (kPa) | 101 | 101 | 101 | 101 | 101 | 101 | 101 | 101 | 101 | 101 |
| Quantity | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) |
| Water | 236 | 251 | 40.0 | 236 | 236 | 40.0 | 20.0 | 20.0 | - | 17.9 |
| Pectin | - | - | 138 | - | - | 138.1 | - | 138 | - | - |
| HCl | - | - | - | - | - | - | - | - | - | - |
| Ethanol | 1681 | 1718 | 98.1 | 1390 | 1390 | 98.1 | 49.0 | 49.0 | - | 43.9 |
| Other | - | 16.3 | 1.81 | - | 1.81 | 1.81 | 0.905 | 0.905 | - | 0.811 |
| Air | - | - | - | - | - | - | - | - | 276 | 276 |
| Total | 1918 | 1985 | 278 | 1626 | 1628 | 278 | 69.9 | 208 | 276 | 339 |

| Stream | 4-17 | 4-18a | 4-18b | 4-19 | 4-20 | 4-21 | 4-22 | 4-23 | 4-24 | 4-25 |
|-----------------|-----------------|-----------------|-----------------|------------------|------------------|-----------------|------------------|-------------------|-----------------|-----------------|
| Description | PEC TO G-201 | PEC TO NODE 3 | PEC TO STORAGE | IMP ETH TO T-401 | IMP ETH TO D-401 | BOTTOMS D-401 | DISTILLATE D-401 | REC ETH TO MT-401 | ETH TO MT-401 | WAT TO MT-401 |
| Temperature (K) | 313 | 298 | 298 | 298 | 350 | 372 | 360 | 298 | 298 | 298 |
| Pressure (kPa) | 101 | 101 | 101 | 101 | 101 | 101 | 142 | 101 | 101 | 101 |
| Quantity | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) | Mass (kg/batch) |
| Water | 2.08 | 2.08 | 2.08 | 904 | 904 | 698 | 206 | 206 | 11.2 | 493 |
| Pectin | 138 | 138 | 138 | 1.39 | 1.39 | 1.39 | - | - | - | - |
| HCl | - | - | - | - | - | - | - | - | - | - |
| Ethanol | 5.10 | 5.10 | 5.10 | 4128 | 4128 | 206 | 3921 | 3921 | 211 | - |
| Other | - | - | - | 364 | 364 | 364 | - | - | - | - |
| Air | - | - | - | - | - | - | - | - | - | - |
| Total | 145 | 145 | 145 | 5397 | 5397 | 1269 | 4128 | 4128 | 223 | 493 |

| Stream | 4-02 | 4-03 | 4-04 | 4-05 | PT-401 |
|-----------------|-------------------|-------------------|-------------------|-------------------|-----------------------|
| Description | PEC TO PT-401 | ETH TO PT-401 | ETH OUT PT-401 | PEC OUT PT-401 | PRECIPITATION TANK |
| Temperature (K) | 298 | 298 | 313 | 313 | |
| Phase (S/L/G) | L | L | L | L | |
| Quantity | Energy (kJ/batch) | Energy (kJ/batch) | Energy (kJ/batch) | Energy (kJ/batch) | Change (ΔQ) |
| Water | 242000 | 293000 | 490000 | 71000 | -26000 |
| Pectin | 224 | - | 2.21 | 218 | 3 |
| Ethanol | - | 78200 | 70400 | 10200 | -2400 |
| Other | 324000 | - | 323000 | 17000 | -16000 |
| Air | - | - | - | - | - |
| Total | 566000 | 371000 | 883000 | 98400 | -44400 |

| Stream | 4-06 | 4-07 | 4-08 | 4-09 | WT-401 |
|-----------------|---------------|---------------|----------------|---------------|-----------------------|
| Description | PEC TO WT-401 | ETH TO WT-401 | ETH OUT WT-401 | PEC TO WT-402 | WASHING TANK |
| Temperature (K) | 313 | 298 | 298 | 298 | |
| Phase (S/L/G) | L | L | L | S/L | |
| Quantity | Energy (kJ) | Energy (kJ) | Energy (kJ) | Energy (kJ) | Change (ΔQ) |
| Water | 71000 | 292000 | 310000 | 49400 | 3600 |
| Pectin | 218 | - | - | 222 | -3 |
| Ethanol | 10200 | 124000 | 127000 | 7230 | -30 |
| Other | 17000 | - | 14600 | 1620 | 780 |
| Air | - | - | - | - | - |
| Total | 98000 | 416000 | 452000 | 58500 | 3500 |

| Stream | 4-14 | 4-15 | 4-16 | 4-17 | DY-401 |
|-----------------|-------------------|-------------------|-------------------|-------------------|-----------------------|
| Description | PEC TO DY-201 | HOT AIR DY-201 | AIR OUT DY-201 | PEC TO G-201 | CONVEYOR DRYER |
| Temperature (K) | 298 | 338 | 298 | 313 | |
| Phase (S/L/G) | S/L | G | G | S | |
| Quantity | Energy (kJ/batch) | Energy (kJ/batch) | Energy (kJ/batch) | Energy (kJ/batch) | Change (ΔQ) |
| Water | 24700 | - | 22100 | 2690 | -90 |
| Pectin | 222 | - | - | 218 | 4 |
| Ethanol | 3610 | - | 3240 | 387 | -20 |
| Other | 809 | - | 725 | 88.3 | -4 |
| Air | - | 7940 | 0.938 | - | 7940 |
| Total | 29000 | 7940 | 26100 | 3380 | 7830 |

| Stream | 4-14 | 4-15 | HEX-401 | HEX-402 | HEX-203 |
|-----------------|-------------------|-------------------|-----------------------|--------------------------------|--------------------------------|
| Description | IMP ETH TO T-401 | IMP ETH TO D-401 | | CONDENSER | REBOILER |
| Temperature (K) | 298 | 350 | | - | - |
| Phase (S/L/G) | L | L | | L/G | L/G |
| Quantity | Energy (kJ/batch) | Energy (kJ/batch) | Change (ΔQ) | Duty (x 10 ⁶ kJ/hr) | Duty (x 10 ⁶ kJ/hr) |
| Water | 1120000 | 1280000 | -160000 | - | - |
| Pectin | 2.24 | 2.12 | 0.116 | - | - |
| Ethanol | 304000 | 332000 | -28000 | - | - |
| Other | 325000 | 374000 | -49000 | - | - |
| Air | - | - | - | - | - |
| Total | 1750000 | 1986000 | -237000 | -5.89 | 5.95 |

F Node 4 Process Control

F.1 Distillation Column D-401

The pressure inside the distillation column D-401 is crucial for the operation of the column. If a pressure gradient is not maintained throughout the distillation column, the ethanol vapours would not flow upwards, and the down-flowing of liquid would significantly affect the product quantity and composition. This pressure gradient is designed to be held constant throughout the usage of column D-401. If the pressure inside the column were to increase above the desired pressure, this can also potentially be a hazard on the plant due to pressure build-up. To counter this, the pressure will be controlled by pressure control valve PSV-426, which will regulate the pressure inside the column by removing excessive gas which would otherwise leave to a pressure build-up. By implementing this, a set pressure point in the column can be maintained.

The temperature inside the column is varied to control the composition of the product. The bottom temperature is set so that the heavy key component (water) remains as a liquid, but the light key component (ethanol) will stay as a gas. The temperature at the bottom of the column is regulated using reboiler HEX-403. The temperature is controlled in the reboiler using medium-pressure steam (mps). By regulating the flowrate of the steam using control loop 434, the temperature near the bottom of the column can be controlled.

The temperature at the top of the column is required so that the heavy key component remains as a liquid and the light key component remains as a gas. This temperature at the top of the column is required to stay at a set point slightly above the boiling point of ethanol. This is controlled by regulating the flowrate of the reflux going back into the column, via control loop 444. Increasing the reflux rate will allow more liquid back into the column, hence decreasing the temperature of the rising gas and reducing the overall temperature at the top of the column.

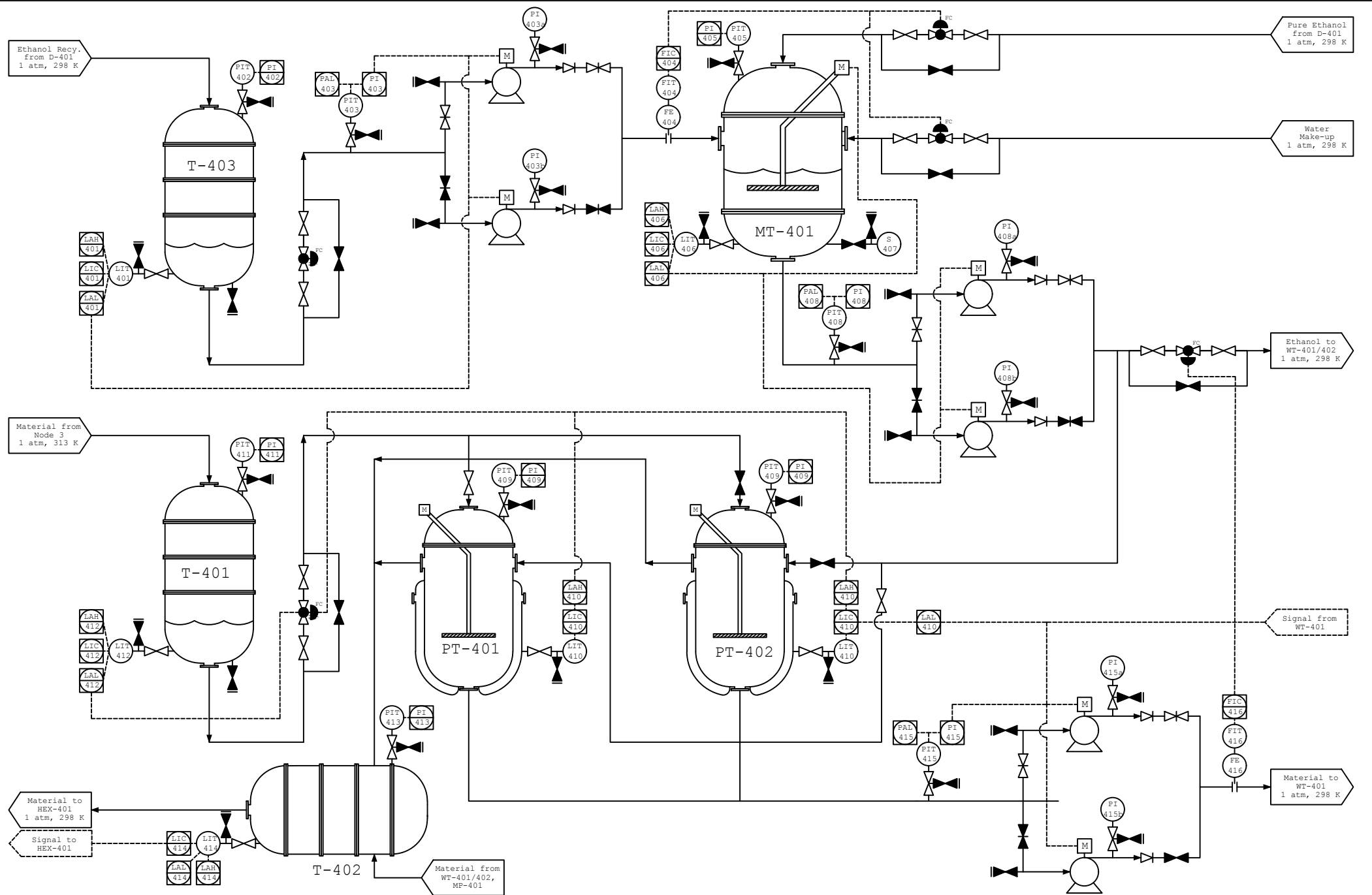
To prevent flooding near the bottom of the column, level control loop 432 has been implemented into the column. This loop is used to control the flowrate of the bottoms product by implementing the pumping and flowrate indication system 433 - if a high level of liquid in the column is detected, the pumps increase their flowrate to remove the excess liquid and flow control valve 433 allows a larger flowrate capacity to remove the liquid. High level and low level alarms are included to indicate to operators when the liquid level inside the column is outside normal operating conditions.

Various sample points are located throughout the column as means of qualitative analysis of the column performance and product composition.

F.2 Ethanol Mixing Tank MT-401

The recycled ethanol from the distillation column requires a make-up stream of ethanol and water to meet the required quantity and quality of ethanol required in the precipitation and washing stages. To create the correct quantity and quality of ethanol, flow control loop 404 first analyses the recycled ethanol being pumped into the mixing tank. This flow controller is connected to two parallel globe valves which then regulate the flow of feedstock ethanol and diluting water into the mixing tank. Once the correct level of ethanol is reached inside the column, the impeller motor is activated via level control loop 406 to begin mixing the three streams. This includes a low level alarm to avoid damage to the impeller, as well as a high level alarm if there is a risk of flooding in the mixer, and also to maintain product quality. The high level alarm acts to increase the pumping rate in pumping system 408, lowering the level in the column.

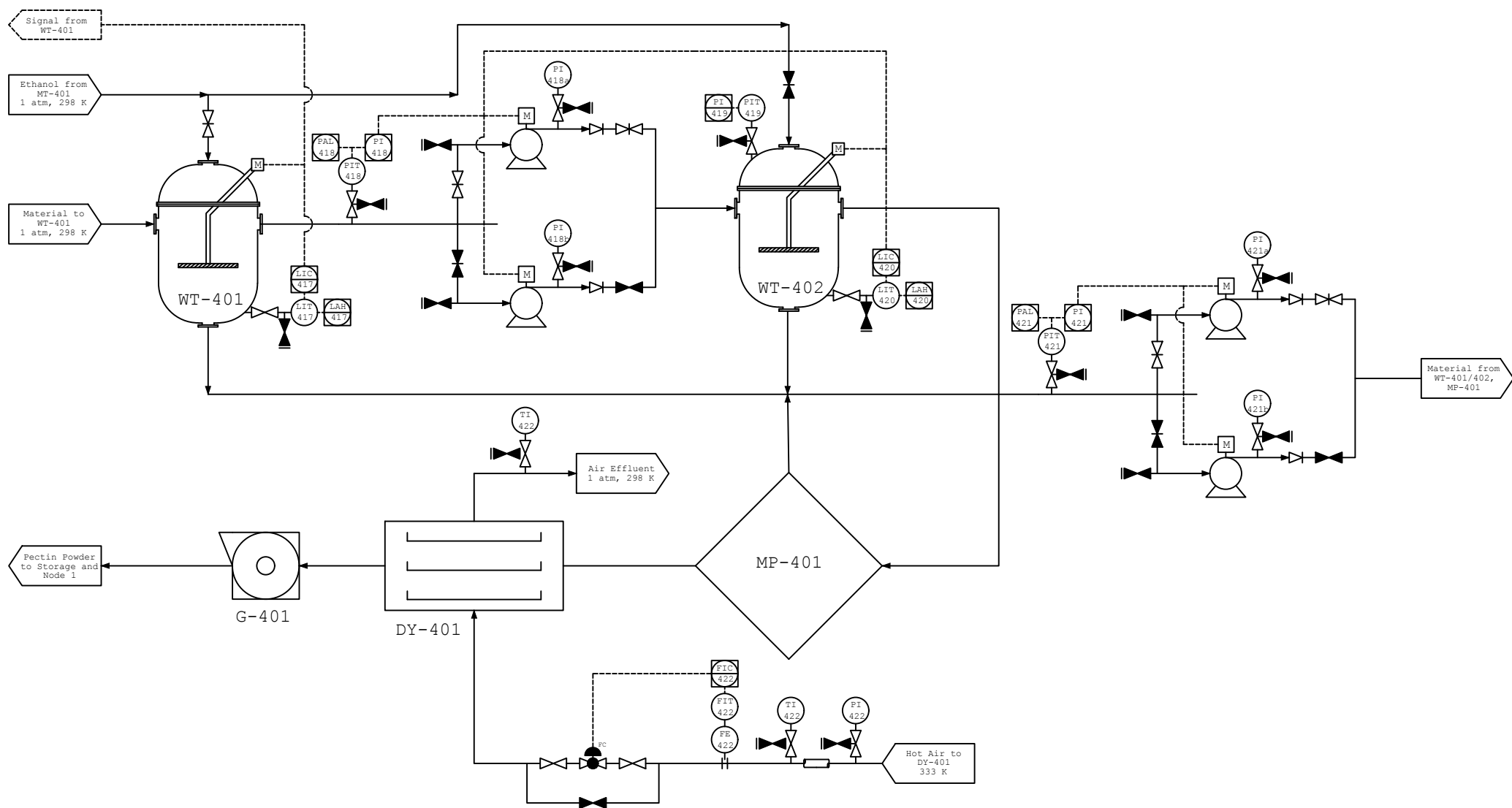
G Piping and Instrumentation Diagram(s)

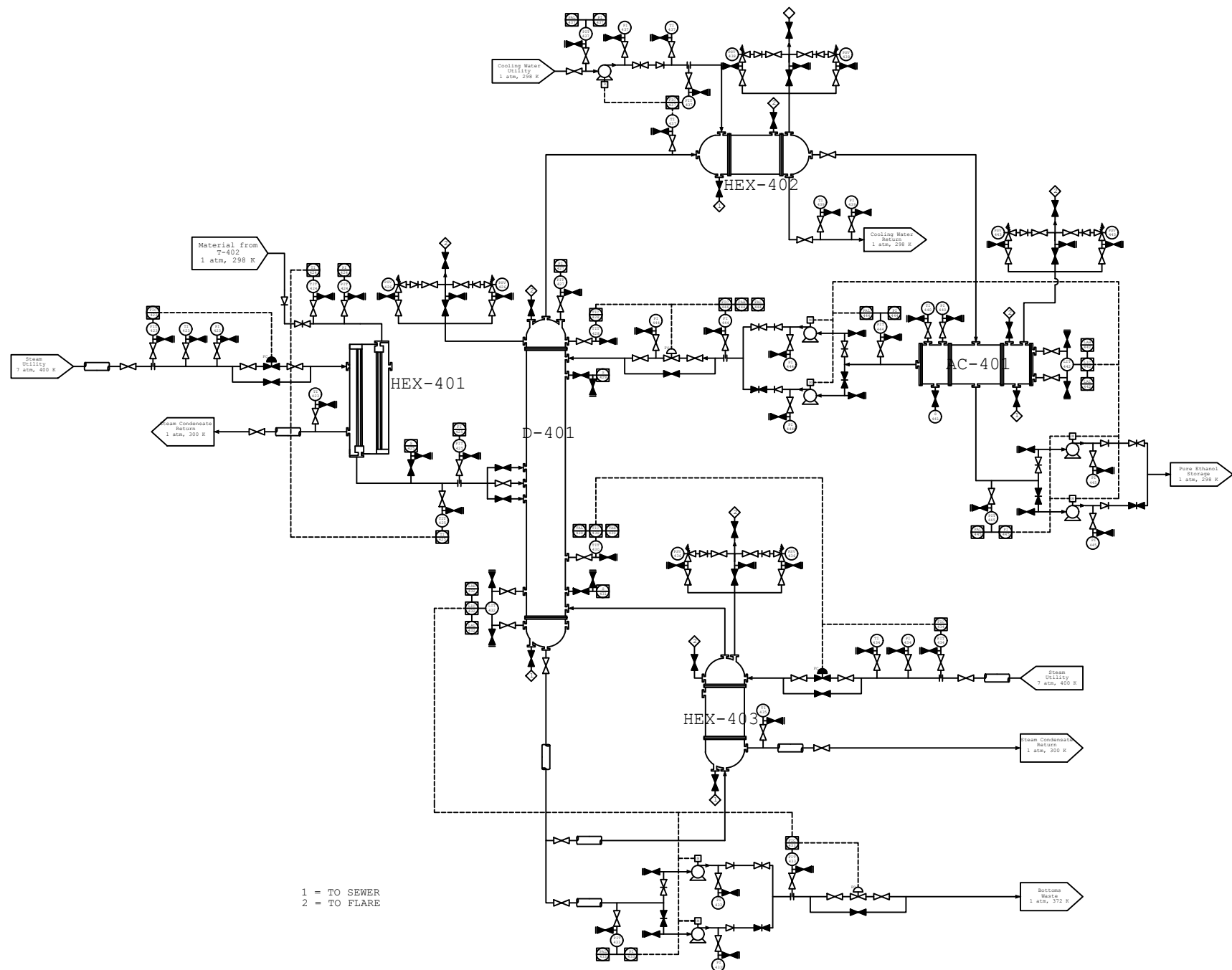


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THE UNIVERSITY OF BIRMINGHAM

| | |
|-------------|--------------|
| DRAWN BY: | Sam Ellis |
| CHECKED BY: | Bea Holloway |
| DATE: | 01/03/2020 |

TITLE OF PROJECT
Conserve Consultancy
Pectin Production
P&ID (part a)





1 = TO SEWER
2 = TO FLARE

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SCHOOL OF ENGINEERING
THE UNIVERSITY OF BIRMINGHAM

DRAWN BY: **Sam Ellis**
CHECKED BY: **Bea Holloway**
DATE: **01/03/2020**

TITLE OF PROJECT
Conserve Consultancy
Pectin Production
P&ID (part c)

H MATLAB Scripts

H.1 Distillation_Design.m

```
%% ETHANOL-WATER DISTILLATION DESIGN SCRIPT
% Written by Sam Ellis Feb 2020.
% VLE data from:
% https://rfmarves.shinyapps.io/IdealVLEcalc/

clear;
clc;
close all;
format short g

%% Mass Balance Data:
filename = '/Users/sam3llis/Desktop/Distillation_Design/MBdata.xlsx';
MB_data = readtable(filename, 'Sheet', 14, 'Range', 'B33:D40', 'ReadVariableNames', false);
MB_data.Properties.VariableNames = {'F', 'B', 'D'};
MB_data.Properties.RowNames = {'Water (HK)', 'Pectin', 'HCL', 'Ethanol (LK)', ...
    'Solids', 'Other', 'Diatomaceous Earth', 'Total'};

X = ['Overall Mass Balance Data for D-201 (kg/batch):']; %#ok<NBRAK>
disp(X); disp(MB_data)

%% Compositions from Mass Balance Data:
Mr_H2O = 18;
Mr_ETH = 46;
Mr_HCL = 36.5;
Mr_GLU = 180;
% Feed:
hours = 4;
F = table2array(MB_data(:, {'F'}));
F_H2O = F(1) / hours;
F_PEC = F(2) / hours;
F_HCL = F(3) / hours;
F_ETH = F(4) / hours;
F_GLU = F(6) / hours;
F_TOT = (sum(F) - F(end)) / hours;

nF_H2O = (F_H2O / Mr_H2O);
nF_HCL = (F_HCL / Mr_HCL);
nF_ETH = (F_ETH / Mr_ETH);
nF_GLU = (F_GLU / Mr_GLU + F_PEC / Mr_GLU);
nF_TOT = nF_H2O + nF_HCL + nF_ETH + nF_GLU;

% Bottoms:
B = table2array(MB_data(:, {'B'}));
B_H2O = B(1);
B_PEC = B(2);
B_HCL = B(3);
B_ETH = B(4);
B_GLU = B(6);
```

```

B_TOT = sum(B) - B(end);

nB_H2O = (B_H2O / Mr_H2O) / hours;
nB_HCl = (B_HCL / Mr_HCL) / hours;
nB_ETH = (B_ETH / Mr_ETH) / hours;
nB_GLU = (B_GLU / Mr_GLU + B_PEC / Mr_GLU) / hours;
nB_TOT = nB_H2O + nB_HCl + nB_ETH + nB_GLU;

% Distillate (Product):
D = table2array(MB_data(:, {'D'}));
D_H2O = D(1);
D_PEC = D(2);
D_HCL = D(3);
D_ETH = D(4);
D_GLU = D(6);
D_TOT = sum(D) - D(end);

nD_H2O = (D_H2O / Mr_H2O) / hours;
nD_HCl = (D_HCL / Mr_HCL) / hours;
nD_ETH = (D_ETH / Mr_ETH) / hours;
nD_GLU = (D_GLU / Mr_GLU + D_PEC / Mr_GLU) / hours;
nD_TOT = nD_H2O + nD_HCl + nD_ETH + nD_GLU;

%% Operating Conditions:
% The main consideration when selecting the column operating pressure will
% be to ensure that the dew point of the distillate is above that which
% can be easily obtained with plant cooling water.

% Top Column Temperature (Dew Point [K], Composition Dependent)
T_op_top = 355.15;
% Bottom Column Temperature (Dew Point [K], Composition Dependent)
T_op_bot = 368.29;

P_op = 101325; % Operating Pressure [Pa]
T_cooling = 303; % Max Cooling Water Temperature [K]

%% Minimum Number of Stages (Fenske Equation)
% Assuming Non-Distributing Assumption.

% Light Key and Heavy Key Concentrations:
nB_H2Oa = nB_H2O + nB_GLU; % Assumed Water in Bottoms

xhk_d = nD_ETH; % Distillate Light Key [kg]
xhk_d = nD_H2O; % Distillate Heavy Key [kg]
xhk_b = nB_ETH; % Bottoms Light Key [kg]
xhk_b = nB_H2Oa; % Bottoms Heavy Key [kg]

% Determine Average Relative Volatility:
a_avg = rel_vol(P_op, T_op_bot, T_op_top);

% Determine Minimum Number of Stages:

```

```

Nmin = log((x1k_d / xhk_d)*(xhk_b / x1k_b)) / log(a_avg);
Nmin = ceil(Nmin);
X = ['Minimum Number of Trays From Fenske Equation: ', num2str(Nmin)];
disp(X)

%% Minimum Reflux Ratio (Underwood Equation)
% Relative volatilities are assumed as constant for the following equation.
% A better estimate can be obtained by replacing the number of stages at
% total reflux in by an estimate of the actual number; a
% value equal to Nmin/0.6 is often used.

Nact = Nmin / 0.6; % Estimate for Actual number of Stages

T_feed = 343; % [K]

%q = 1;
q = findq(P_op, T_feed); % Use Function 'findq' to determine q ratio.

theta = findtheta(q, nF_H2O, nF_ETH, nF_GLU, nF_TOT); % findtheta function to find theta

Rmin = findRmin(theta, nD_H2O, nD_ETH, nD_GLU, nD_TOT);
Rmin = round(Rmin, 3, 'significant');
X = ['Minimum Reflux Ratio From Underwood Equation: ', num2str(Rmin)];
disp(X)

% Find Rmin:
%Rmin = ((a_avg*(nD_ETH/nD_TOT))/(a_avg-theta))-1;

%% Actual Reflux Ratio Ropt:
% As a first approximation, 1.5 times the minimum reflux is often used.

Ropt = Rmin * 1.5;
Ropt = round(Ropt, 3, 'significant');
X = ['Optimum Reflux Ratio First Approximation: ', num2str(Ropt)];
disp(X)

%% Specimen calculation for Ropt (Erbar-Maddox/Molokanov Correlation):
Rmingrad = Rmin / (Rmin + 1);
Rgrad = Ropt / (Ropt + 1);

% Using Erbar-Maddox Correlation Graph:
NminNratio = 0.62; % WILL CHANGE WITH DIFFERENT OPTIMISATIONS

% Know Nmin, so can find N:
N_Erbar = Nmin / NminNratio;
N_Erbar = ceil(N_Erbar);
X = ['Number of Stages using Erbar-Maddox Correlation: ', num2str(N_Erbar)];
disp(X)

% Verify Using Molokanov Correlation:
syms N_Molo

```

```

X = (Ropt - Rmin) / (Ropt + 1);
(N_Molo - Nmin) / (N_Molo + 1);
Y = ( ...
    (N_Molo - Nmin) / (N_Molo + 1) ...
    == 1 - exp((1 + 54.4 * X)/(11 + 117.2 * X)*(X - 1)/X^0.5) ...
);
N_Molo = double(vpasolve(Y, N_Molo));
N_Molo = ceil(N_Molo);
X = ['Number of Stages using Molokanov Correlation: ', num2str(N_Molo)];
disp(X)

% Take Average of Both Correlations:
N_avg = ceil((N_Erbar + N_Molo)/2);
X = ['Average Number of Stages Using Correlations: ', num2str(N_avg)];
disp(X)

%% Plate Efficiency:
% Table 11.1 in C11 can be used to determine the Murphee plate efficiency
% for a water-ethanol system. Assuming sieve plates are used.

Emv = 0.9; % Murphee Plate Efficiency
X = ['Murphee Plate Efficiency: ', num2str(Emv)];
disp(X)

% Overall column efficiency and Murphee plate efficiency are related by the
% following equation (Lewis 1936), however not very reliable.
% The O'Connell relation can also be used to estimate the overall column
% efficiency:
...
a_WAT = 2.414E-05; % [Pa s]
b_WAT = 247.8; % [K]
c_WAT = 140; % [K]
mu_WAT = a_WAT * 10^(b_WAT / (T_feed - c_WAT)) * 1000; % Water Viscosity [mN s]

a_ETH = -7.37146;
b_ETH = 2770.25;
c_ETH = 74.6787;
mu_ETH = exp(a_ETH+b_ETH/(c_ETH + T_feed)); % Ethanol Viscosity [mN s]

mu_GLU = 0.520;

mu_avg = ( ...
    (nF_H2O / nF_TOT) * mu_WAT + ...
    (nF_ETH / nF_TOT) * mu_ETH + ...
    (nF_GLU / nF_TOT) * mu_GLU ...
); % Average Viscosity of Solution [mNs/m^2]

Eo = (51 - 32.5 * log(mu_avg*a_avg)) / 100; % Overall Column Efficiency
Eo = round(Eo, 3, 'significant');
X = ['Overall Column Efficiency (O Connell Relation): ', num2str(Eo)];
disp(X)

```

```

N_act = (N_avg - 1) / Eo;
N_act = ceil(N_act);
X = [ ...
    'When the Reflux Ratio is ', num2str(Ropt), ...
    ', Number of Ideal Stages (Excluding Reboiler) = ', num2str(N_avg-1), ...
    ', so Number of Actual Stages: ', num2str(N_act), ...
    ];
disp(X)

%% Feed Point Location (Kirkbride Empirical Equation):
xhk_f = nF_ETH / nF_TOT;
xhk_f = nF_H2O / nF_TOT;

% Ratio Nr/Ns:
logNrNsratio = 0.206 * log((nB_TOT / nD_TOT)*(xhk_f / xlk_f)*(xlk_b / xhk_b)^2);
logNrNsratio = -0.1053;
NrNsratio = 10^(logNrNsratio);

% For Specific Ropt and N:
syms Ns
Nr = Ns * NrNsratio;
eqn = Nr + Ns == N_act + 1;
Ns = double(vpasolve(eqn, Ns));
Ns = round(Ns);

X = ['Number of Stages, Excluding the Reboiler: ', num2str(N_act)];
disp(X)
X = ['Number of Stages Below the Feed, Including the Reboiler', ...
    ' (Position of Feedpoint for Separation): ', num2str(Ns)];
disp(X)

```

H.2 findq.m

```

function q = findq(P_op, T_feed)
% Function will find the ratio q for distillation calculations for an
% ethanol-water system. Note that there is only data for systems at
% atmospheric pressure and that the enthalpy values given are dependent on
% the mole fraction of ethanol present in the feed.
% Written by Sam Ellis Feb 2020.
% Data from: http://www.separationprocesses.com/Distillation/DT\_Ch04k.htm
patm = 101325; %atmos pressure [pa]
if P_op == patm && T_feed == 343 % [K]
    Hf = 350; % Enthalpy of Feed, Evaluated at Feed Temperature
    Hv = 1300; % Enthalpy of Vapour [kJ/kg]
    Hl = 250; % Enthalpy of Liquid
    q = (Hv - Hf) / (Hv - Hl);
else
    X = ['Data Not Found for Operating Pressure or Temperature of Feed (findq function)']
end
end

```

H.3 rel_vol.m

```
function a_avg = rel_vol(P_op, T_op_bot, T_op_top)
% Function calculates the relative volatility of specified components
% relative to water. The equilibrium constants K at the top and bottom of
% the column are first calculated, and from this the relative volatility
% can be determined.
% Written by Sam Ellis Feb 2020.

% Data from: http://polymer.sut.ac.ir/People/Courses/50/Acentric%20factor.pdf

% Water Parameters:
Tc_H2O = 647; % Critical Temperature [K]
Pc_H2O = 22064; % Critical Pressure [kPa]
w_H2O = 0.344; % Acentric Factor [-]

% Ethanol Parameters:
Tc_ETH = 513.9; % Critical Temperature [K]
Pc_ETH = 6250; % Critical Pressure [kPa]
w_ETH = 0.644; % Acentric Factor [-]

% Glucose Parameters:
Tc_GLU = 1011.14; % Critical Temperature [K]
Pc_GLU = 6200; % Critical Pressure [kPa]
w_GLU = 2.5674; % Acentric Factor [-]

% HCl Parameters:
Tc_HCL = 324.65; % Critical Temperature [K]
Pc_HCL = 8.36E-06; % Critical Pressure [kPa]
w_HCL = 0.134; % Acentric Factor [-]

% Calculate Equilibrium Constants Using the Wilson Correlation (1968):
K_lk_top = (Pc_ETH / P_op) * exp(5.37*(1 + w_ETH)*(1 - (Tc_ETH / T_op_top)));
K_hk_top = (Pc_H2O / P_op) * exp(5.37*(1 + w_H2O)*(1 - (Tc_H2O / T_op_top)));

K_lk_bot = (Pc_ETH / P_op) * exp(5.37*(1 + w_ETH)*(1 - (Tc_ETH / T_op_bot)));
K_hk_bot = (Pc_H2O / P_op) * exp(5.37*(1 + w_H2O)*(1 - (Tc_H2O / T_op_bot)));

K_glu_top = (Pc_GLU / P_op) * exp(5.37*(1 + w_GLU)*(1 - (Tc_GLU / T_op_top)));

K_hcl_top = (Pc_HCL / P_op) * exp(5.37*(1 + w_HCL)*(1 - (Tc_HCL / T_op_top)));

% For finding theta:
a_feed_eth = K_lk_top / K_hk_top;
a_feed_wat = 1;
a_feed_glu = K_glu_top / K_hk_top;
a_feed_hcl = K_hcl_top / K_hk_top;

% Determine Relative Volatility:
a_lkhk_top = K_lk_top / K_hk_top; % Relative Volatility at Top of Column
a_lkhk_bot = K_lk_bot / K_hk_bot; % Relative Volatility at Bottom of Column
```

```
a_avg = sqrt(a_lkhk_top*a_lkhk_bot); % Average Relative Volatility

end
```

H.4 findtheta.m

```
function theta = findtheta(q, nF_H2O, nF_ETH, nF_GLU, nF_TOT)
% function finds an approximate theta for a given q ratio input.
% written by sam ellis Mar 2020.

% Relative Volatilities of Individual Components:
a_H2O = 1;
a_ETH = 2.06;
a_GLU = 0;

% Solve eqn for theta:
target = q - 1;
x = [nF_H2O / nF_TOT; nF_ETH / nF_TOT; nF_GLU / nF_TOT];
a = [a_H2O; a_ETH; a_GLU];
ax = a .* x;

syms theta
eqn = ax ./ (a - theta);

eqnsum = sum(eqn) == target;
theta = double(vpasolve(eqnsum, theta));
theta = theta(1);

end
```

H.5 findRmin.m

```
function Rmin = findRmin(theta, nD_H2O, nD_ETH, nD_GLU, nD_TOT)
% Written by Sam Ellis March 2020

% Relative Volatilities of Individual Components:
a_H2O = 1;
a_ETH = 2.06;
a_GLU = 0;

xd = [nD_H2O / nD_TOT; nD_ETH / nD_TOT; nD_GLU / nD_TOT];
a = [a_H2O; a_ETH; a_GLU];
ax = a .* xd;

for i = 1:length(xd)
    eqn(i) = ax(i) / (a(i) - theta);
end

Rmin = sum(eqn) - 1;

end
```


H.6 Plate_Design.m

```
% m-file for Distillation Plate Design.
% Written by Sam Ellis Mar 2020.

clear;
clc;
close all

%% Mass Balance Data:
filename = '/Users/sam3llis/Desktop/Distillation_Design/MBdata.xlsx';
MB_data = readtable(filename, 'Sheet', 14, 'Range', 'B33:D40', 'ReadVariableNames', false);
MB_data.Properties.VariableNames = {'F', 'B', 'D'};
MB_data.Properties.RowNames = {'Water (HK)', 'Pectin', 'HCL', 'Ethanol (LK)', ...
    'Solids', 'Other', 'Diatomaceous Earth', 'Total'};
X = ['Overall Mass Balance Data for D-201 (kg/batch):'];
disp(X); disp(MB_data)

hours = 4;
Mr_H2O = 18;
Mr_ETH = 46;
Mr_HCL = 36.5;
Mr_GLU = 180;

% Feed:
F = table2array(MB_data(:, {'F'}));
F_H2O = F(1) / hours;
F_PEC = F(2) / hours;
F_HCL = F(3) / hours;
F_ETH = F(4) / hours;
F_GLU = F(6) / hours;
F_TOT = (sum(F) - F(end)) / hours;

nF_H2O = (F_H2O / Mr_H2O);
nF_HCL = (F_HCL / Mr_HCL);
nF_ETH = (F_ETH / Mr_ETH);
nF_GLU = (F_GLU / Mr_GLU + F_PEC / Mr_GLU);
nF_TOT = nF_H2O + nF_HCL + nF_ETH + nF_GLU;

% Bottoms:
B = table2array(MB_data(:, {'B'}));
B_H2O = B(1) / hours;
B_PEC = B(2) / hours;
B_HCL = B(3) / hours;
B_ETH = B(4) / hours;
B_GLU = B(6) / hours;
B_TOT = (sum(B) - B(end)) / hours;

nB_H2O = (B_H2O / Mr_H2O);
nB_HCL = (B_HCL / Mr_HCL);
nB_ETH = (B_ETH / Mr_ETH);
nB_GLU = (B_GLU / Mr_GLU + B_PEC / Mr_GLU);
```

```

nB_TOT = nB_H2O + nB_HCl + nB_ETH + nB_GLU;

% Distillate:
D = table2array(MB_data(:, {'D'}));
D_H2O = D(1) / hours;
D_PEC = D(2) / hours;
D_HCL = D(3) / hours;
D_ETH = D(4) / hours;
D_GLU = D(6) / hours;
D_TOT = (sum(D) - D(end)) / hours;

nD_H2O = (D_H2O / Mr_H2O);
nD_HCl = (D_HCL / Mr_HCL);
nD_ETH = (D_ETH / Mr_ETH);
nD_GLU = (D_GLU / Mr_GLU + D_PEC / Mr_GLU);
nD_TOT = nD_H2O + nD_HCl + nD_ETH + nD_GLU;

%% Flowrates:
R_opt = 4.00; % optimum reflux ratio

% Assume feed is saturated liquid, so:
L_above = R_opt * nD_TOT; % liquid flow above feed [kmol/h]
L_below = R_opt * nD_TOT; % liquid flow below feed [kmol/h]
V = nD_TOT * (1 + R_opt); % vapour rate [kmol/h]

%% Physical Properties:
N_actual = 21; % actual number of distillation stages
st_liq = 0.02; % liquid surface tension [N/m]

% Assume pressure drop per plate is 100 mm water:
drop = 100; % pressure drop per plate [mm]
rho_H2O = 1000; % water density [kg/m^3]
g = 9.81; % gravity [m/s^2]

DeltaP_column = (drop * 10^(-3)) * rho_H2O * g * N_actual; % column pressure drop [Pa]
top_pressure = 101325; % top column pressure [Pa]
bot_pressure = top_pressure + DeltaP_column; % bottom column pressure [Pa]

% Bottoms Temperature (x \degC)
rho_v_bot = 2.027886; % vapour density [kg/m^3]
rho_l_bot = 955.537; % liquid density [kg/m^3]
Mr_top = D_H2O / D_TOT * Mr_H2O + D_HCL / D_TOT * Mr_HCL + ...
    D_ETH / D_TOT * Mr_ETH + D_GLU / D_TOT * Mr_GLU;
% from: https://pubchem.ncbi.nlm.nih.gov/compound/Ethanol#section=Vapor-Density

% Distillate Temperature (x \degC)
rho_v_top = 2.027886; % vapour density [kg/m^3]
rho_l_top = 736.919; % liquid density [kg/m^3]
Mr_bot = B_H2O / B_TOT * Mr_H2O + B_HCL / B_TOT * Mr_HCL + ...
    B_ETH / B_TOT * Mr_ETH + B_GLU / B_TOT * Mr_GLU;

```

```

%% Flooding Velocity:
% The flooding velocity can be estimated from the correlation given by
% Fair (1961).

F_lv_top = L_above / V * sqrt(rho_v_top/rho_l_top); % top liquid-vapour flow factor
F_lv_bot = L_below / V * sqrt(rho_v_bot/rho_l_bot); % bot liquid-vapour flow factor

% Take plate spacing L_t = 0.3 [m]:
K1_top = 0.065; % top constant obtained from Sinnott Fig. 11.34
K1_bot = 0.065; % bottom constant obtained from Sinnott Fig. 11.34

A_column = 1; % total column cross-sectional area [m^2]
A_downcomer = 0.12 * A_column; % cross-sectional area of downcomer [m^2]
A_net_top = A_column - A_downcomer; % net area available for vapour-liquid disengagement [m^2]
A_active_top = A_column - 2 * A_downcomer; % bubbling area [m^2]
A_hole = 0.10 * A_column; % hole area, the total area of all the active holes [m^2]
A_perforated = 1; % perforated area (including blanked areas) [m^2]
A_apron = 1; % the clearance area under the downcomer apron [m^2]

% For different hole:active area ratios and liquid surface tensions:
if A_hole / A_active_top >= 0.10
    K1_top = (K1_top * 1.0) * (st_liq / 0.02)^0.2;
    K1_bot = (K1_bot * 1.0) * (st_liq / 0.02)^0.2;
elseif A_hole / A_active_top >= 0.08 && A_hole / A_active_top < 0.10
    K1_top = K1_top * 0.9 * (st_liq / 0.02)^0.2;
    K1_bot = K1_bot * 0.9 * (st_liq / 0.02)^0.2;
elseif A_hole / A_active_top >= 0.06 && A_hole / A_active_top < 0.08
    K1_top = K1_top * 0.8 * (st_liq / 0.02)^0.2;
    K1_bot = K1_bot * 0.8 * (st_liq / 0.02)^0.2;
end

u_flooding_top = K1_top * sqrt((rho_l_top - rho_v_top)/rho_v_top); % top flooding velocity [m/s]
u_flooding_bot = K1_bot * sqrt((rho_l_bot - rho_v_bot)/rho_v_bot); % bottom flooding velocity [m/s]

% Design for 85 per cent flooding at maximum flowrate:
u_top = 0.85 * u_flooding_top; % top design velocity [m/s]
u_bot = 0.85 * u_flooding_bot; % bottom design velocity [m/s]

Q_top = (V * Mr_top) / (rho_v_top * 3600); % top maximum volumetric flow rate [m^3/s]
Q_bot = (V * Mr_bot) / (rho_v_bot * 3600); % bottom maximum volumetric flowrate [m^3/s]

%% Net Area Required:
A_net_bot = Q_bot / u_bot; % bottom net area available for vapour-liquid disengagement [m^2]

%% Estimate Column Cross-Sectional Area:
% As a first iteration, will take downcomer area as 12 per cent of the
% net area required:
downcomerarea = 0.12;
A_column_top = A_net_top / (1 - downcomerarea); % top total column cross-sectional area [m^2]
A_column_bot = A_net_bot / (1 - downcomerarea); % bottom total column cross-sectional area [m^2]

```

```

% Revision of column total area to change column diameter:
revision = 0.5;
A_column_top = ...
    A_net_top / (1 - downcomerarea) + revision; % top total column cross-sectional area [m^2]

%% Estimate Column Diameter:
D_column_top = sqrt(A_column_top*4/pi);
D_column_bot = sqrt(A_column_bot*4/pi);

% Will use the same diameter for both above and below the feed, but reduce
% the perforated area of the plates where necessary:
D_column = max(D_column_top, D_column_bot);
% STANDARD SIZE BEFORE CARRYING ON?

%% Liquid Flow Arrangement:
Q_max_liq = (L_below * Mr_bot) / (3600 * rho_l_bot); % maximum volumetric liquid rate [m^3/s]

% From Sinnott Fig. 11.35, a SINGLE-PASS PLATE can be used.

%% Provisional Plate Design (BOT):
A_downcomer_top = 2 * downcomerarea * A_column_top;
A_net_top = A_column_top - A_downcomer_top;
A_active_top = A_column_top - 2 * A_downcomer_top;
A_hole_top = 0.10 * A_active_top;
weir_length = 0.77 * D_column;
weir_height = 50;
hole_diameter = 5;
plate_thickness = 5;

Parameter_top = {'Column Diameter, Dc:', 'Downcomer Area, Ad:', ...
    'Net Area, An:', 'Active Area, Aa:', 'Hole Area, Ah', ...
    'Weir Length', 'Weir Height', 'Hole Diameter', ...
    'Plate Thickness'}';
Value_top = [D_column, A_downcomer_top, A_net_top, A_active_top, ...
    A_hole_top, weir_length, weir_height, hole_diameter, ...
    plate_thickness]';
Value_top = num2cell(Value_top);
Units_top = {'m', 'm^2 at 12 per cent Ac', 'm^2', 'm^2', ...
    'm^2 at 10 per cent Ah', 'm', 'mm', 'mm', 'mm'}';

x = table([Parameter_top, Value_top, Units_top]);
x.Properties.VariableNames = {'Provisional Plate Design (BOT)'};
X = ['First Iteration:'];
disp(X); disp(x)

%% Check Weeping:
m_max_liq = (L_below * Mr_bot) / 3600; % maximum liquid rate [kg/s]
m_min_liq = 0.70 * m_max_liq; % minimum liquid rate at 70 per cent turndown [kg/s]

h_ow_max = 750 * (m_max_liq / (rho_l_bot * weir_length))^(2 / 3); % max weir liquid crest [m]
h_ow_min = 750 * (m_min_liq / (rho_l_bot * weir_length))^(2 / 3); % min weir liquid crest [m]

```

```

X = ['At minimum rate, h_w + h_ow = ', num2str(weir_height), ' + ', ...
    num2str(h_ow_min), ' = ', num2str(weir_height+h_ow_min), ' mm.'];
disp(X)

K2 = 30.2; % constant from Sinnott Fig. 11.37
A_column = (pi * (D_column)^2) / 4; % total column cross-sectional area [m^2]
A_hole = 0.10 * A_column;

u_vap_min_h = (K2 - 0.90 * (25.4 - hole_diameter)) / (rho_v_bot)^(1 / 2); % minimum vapour v
u_vap_min_actual = (0.70 * Q_bot) / A_hole; % actual minimum vapour velocity [m/s]
if u_vap_min_actual < u_vap_min_h
    X = ['Minimum operating rate leads to weeping at the bottom of the column.'];
    Y = ['Reduce hole area to 7 per cent of active area:'];
    disp(X); disp(Y)
    A_hole = 0.07 * A_column;
    u_vap_min_actual = (0.70 * Q_bot) / A_hole;
    if u_vap_min_actual < u_vap_min_h
        X = ['Minimum operating rate leads to weeping at the bottom of the column.'];
        Y = ['Reduce hole area to 5 per cent of active area:'];
        disp(X); disp(Y)
        A_hole = 0.05 * A_column;
        u_vap_min_actual = (0.70 * Q_bot) / A_hole;
    end
end
else
end

X = ['Hole cross-sectional area [m^2]: '];
disp(X); disp(A_hole)
X = ['Minimum vapour velocity through holes [m/s]: '];
disp(X); disp(u_vap_min_h)
X = ['Actual minimum vapour velocity [m/s]: '];
disp(X); disp(u_vap_min_actual)

%% Plate Pressure Drop:
u_vap_max = Q_bot / A_hole; % maximum vapour velocity through holes [m/s]
platehole = plate_thickness / hole_diameter;
A_rat = A_hole / A_active_top;
Co = 0.84; % constant from Sinnott Fig. 11.42

X = ['For plate thickness/hole diameter = ', num2str(platehole), ', and'];
Y = ['Ah/Ap = Ah/Aa = ', num2str(A_rat), ', C0 = ', num2str(Co), ' from Sinnott Fig. 11.42.'];
disp(X); disp(Y)

h_d = 51 * (u_vap_max / Co)^2 * (rho_v_bot / rho_l_bot); % dry plate pressure drop [mm liq]
h_r = (12.5 * 10^3) / rho_l_bot; % residual head [mm liq]
h_tot = h_d + (weir_height + h_ow_max) + h_r; % total plate pressure drop [mm liq]

% 100 mm liq was used to calculate the basec pressure. calculation could be
% repeated with a revised estimate but the small change in physical
% properties will have little effect on the plate design.

```

```

%% Downcomer Liquid Back-Up:
apron_height = weir_height - 10; % height of the arpon [mm]
A_apron = apron_height * 10^(-3) * weir_length; % clearance area under the downcomer [m^2]

if A_apron <= A_downcomer_top
    head_downcomer = 166 * (m_max_liq / rho_l_bot * A_apron)^2;
elseif A_apron > A_downcomer_top
    head_downcomer = 166 * (m_max_liq / rho_l_bot * A_downcomer_top)^2;
end

tray_spacing = 0.3; % spacing of trays [m]
h_backup = (weir_height + h_ow_max) + h_tot + head_downcomer; % back-up height in downcomer
max_acceptance = 0.5 * (tray_spacing * 10^3 * weir_height);

if h_backup < max_acceptance
    disp('Tray spacing acceptable.')
else
    disp('Tray spacing error - revise `tray_spacing` variable.')
end

residence_time = (A_downcomer * h_backup * 10^(-3) * rho_l_bot) / m_max_liq; % residence time

if residence_time > 5
    disp('Residence time satisfactory.')
else
    disp('Residence time error - revise `residence_time` variable.')
end

%% Check Entrainment:
u_v = Q_bot / A_net_top; % vapour velocity [m/s]
percent_flooding = u_v / u_flooding_bot;

if percent_flooding > 0.85
    disp('Flooding too high - revise column total surface area to change column diameter.')
else
    disp('Flooding satisfactory.')
end

X = ['As F_LV = ', num2str(F_lv_bot), ', percent floodng = ', num2str(percent_flooding)];
Y = ['therefore fractional entrainment from Sinnott Fig. 11.36 = 0.05, well below 0.1.'];
disp(X); disp(Y)

%% Perforated Area:
% Allow 50 mm unperforated strip round plate edge and 50 mm wide calming zones.
wLDc_ratio = weir_length / D_column;
theta_c = 87;
X = ['Weir length to column diameter ratio = ', num2str(wLDc_ratio), ...
    ', theta_c = ', num2str(theta_c), ' from Sinnott Fig 11.40.'];
disp(X)

```

```

edge_unperforated = 50; % [mm]
calming_zone = 50; % [mm]

angle = 180 - theta_c;
l_unperforated = ( ...
    (D_column - (edge_unperforated / 1000)) ...
    * pi * angle / 180); % length of unperforated edge strips [m]
A_unperforated = ( ...
    l_unperforated * (edge_unperforated / 1000)...
    ); % area of unperforated edge strips [m^2]

l_calming_zone_mean = ( ...
    weir_length + (calming_zone / 1000) ...
    ); % mean length of calming zone [m]
A_calming_zone = ( ...
    2 * (l_calming_zone_mean * (calming_zone / 1000))...
    ); % area of calming zones [m^2]

A_perforations = (...
    A_active_top - A_unperforated - A_calming_zone ...
    ); % total area for perforations [m^2]
Ah_Apratio = A_hole / A_perforations; % hole area to perforation area ratio

% USE FIGURE Sinnott Fig. 11.41
lp_dh_ratio = 2.6;
D_hole = 5 / 1000;
area_one_hole = (pi * D_hole^2) / 4; % hole diameter of 5 mm
number_holes = round(A_hole/area_one_hole);

%% Plate Specification (BOT):
A_downcomer_top = downcomerarea * A_column_top;
A_net_top = A_column_top - A_downcomer_top;
A_active_top = A_column_top - 2 * A_downcomer_top;
A_hole_top = 0.10 * A_active_top;
weir_length = 0.77 * D_column;
weir_height = 50;
hole_diameter = 5;
plate_thickness = 5;

Parameter_top = {'Column Diameter, Dc:', 'Downcomer Area, Ad:', ...
    'Net Area, An:', 'Active Area, Aa:', 'Hole Area, Ah', ...
    'Weir Length', 'Weir Height', 'Hole Diameter', ...
    'Plate Thickness'}';
Value_top = [D_column, A_downcomer_top, A_net_top, A_active_top, ...
    A_hole_top, weir_length, weir_height, hole_diameter, ...
    plate_thickness]';
Value_top = num2cell(Value_top);
Units_top = {'m', 'm^2 at 12 per cent Ac', 'm^2', 'm^2', ...
    'm^2 at 10 per cent Ah', 'm', 'mm', 'mm', 'mm'}';

x = table([Parameter_top, Value_top, Units_top]);

```

```

x.Properties.VariableNames = {'Plate Specification (BOT)'};
disp(X); disp(x)
N_trays = 21;
length_column = (tray_spacing + plate_thickness / 1000) * N_trays + 2;

```

H.7 Costing.m

```

% m-file to find cost of equipment.
% Written by Sam Ellis Mar 2020

clear;
clc;
close all;
format long g

equipment.names = (["Propeller"; "Spiral ribbon mixer"; "Static mixer"; ...
    "Boiler - Packaged"; "Boiler - Field erected"; "Centrifuge - High speed disk"; ...
    "Centrifuge - Atmospheric suspended basket"; "Belt - 0.5m wide"; ...
    "Belt - 1.0m wide"; "Bucket elevator - 0.5m bucket"; ...
    "Crusher - Reversible hammer mill"; "Crusher - Pulveriser"; ...
    "Dryer - Direct contact rotary"; "Dryer - Atmospheric tray batch"; ...
    "Dryer - Spray dryer"; "Evaporator - Vertical tube"; ...
    "Evaporator - Agitated falling film"; "Filter - Plate and Frame"; ...
    "Filter - Vacuum drum"; "Furnace - Cylindrical"; "Furnace - Box"; ...
    "Centrifugal pump"; "Explosion proof motor"; "Condensing steam turbine"; ...
    "Tank - Floating roof"; "Tank - Cone roof"; "Sieve trays"; "Valve trays"; ...
    "Bubble cap trays"; 'Pressure vessel - Vertical cs'; ...
    'Pressure vessel - Horizontal cs'; 'Pressure vessel - Vertical 304 ss'; ...
    'Pressure vessel - Horizontal 304 ss'; "Reactor - Jacketed, agitated"; ...
    "U-tube shell and tube"; "Kettle reboiler"]);
disp(equipment.names)

prompt = {'Enter Equipment Type'};
dlgtitle = 'Equipment Type';
definput = {'Propeller'};
opts.Interpreter = 'tex';
equip = string(inputdlg(prompt, dlgtitle, [1, 40], definput, opts));

cost = equipment_cost(equip);
cost = round(cost, 3, 'significant');

X = ['The cost of the ', num2str(equip), ' is (2018 price): ($)'];
disp(X); disp(cost)
Y = ['±30% within the accuracy of the method.', ...
    ' U.S. Gulf Coast basis, January 2007.'];
disp(Y)

```


H.8 Equipment_Cost.m

```
% Function for purchased equipment cost for common plant equipment.
% Data given in (Sinnott, 2020), Chapter 6.
% The function uses the correlation  $C_e = a + bS^n$ , where  $C_e$  is the
% purchased equipment cost on a U.S. Gulf Coast basis, Jan. 2007.
% ISBL method is used to calculate the fixed capital cost.
% Written by Sam Ellis Mar 2020.
```

```
function cost = equipment_cost(equip)
```

```
%% Equipment Selection:
```

```
% Data:
```

```
equipment.names = ("Propeller"; "Spiral ribbon mixer"; "Static mixer"; ...
    "Boiler - Packaged"; "Boiler - Field erected"; "Centrifuge - High speed disk"; ...
    "Centrifuge - Atmospheric suspended basket"; "Belt - 0.5m wide"; ...
    "Belt - 1.0m wide"; "Bucket elevator - 0.5m bucket"; ...
    "Crusher - Reversible hammer mill"; "Crusher - Pulveriser"; ...
    "Dryer - Direct contact rotary"; "Dryer - Atmospheric tray batch"; ...
    "Dryer - Spray dryer"; "Evaporator - Vertical tube"; ...
    "Evaporator - Agitated falling film"; "Filter - Plate and Frame"; ...
    "Filter - Vacuum drum"; "Furnace - Cylindrical"; "Furnace - Box"; ...
    "Centrifugal pump"; "Explosion proof motor"; "Condensing steam turbine"; ...
    "Tank - Floating roof"; "Tank - Cone roof"; "Sieve trays"; "Valve trays"; ...
    "Bubble cap trays"; 'Pressure vessel - Vertical cs'; ...
    'Pressure vessel - Horizontal cs'; 'Pressure vessel - Vertical 304 ss'; ...
    'Pressure vessel - Horizontal 304 ss'; "Reactor - Jacketed, agitated"; ...
    "U-tube shell and tube"; "Kettle reboiler"]);
equipment.a = [15000; 27000; 500; 106000; 110000; 50000; 57000; 36000; 40000; 15000; ...
    60000; 14000; 13000; 8700; 350000; 280; 75000; 110000; -63000; 68500; 37000; 6900; ...
    -950; -12000; 97000; 5000; 110; 180; 290; 10000; 8800; 15000; 11000; 53000; 24000; ...
    25000];
equipment.b = [990; 110; 1030; 8.7; 45; 423000; 660; 640; 1160; 2300; 640; 590; 9100; ...
    6800; 1900; 30500; 56000; 77000; 80000; 93000; 95000; 206; 1770; 1630; 2800; 1400; ...
    380; 340; 550; 29; 27; 68; 63; 28000; 46; 340];
equipment.n = [1.05; 2.0; 0.4; 1.0; 0.9; 0.7; 1.5; 1.0; 1.0; 1.0; 1.0; 0.5; 0.9; 0.5; ...
    0.7; 0.55; 0.75; 0.5; 0.3; 0.8; 0.8; 0.9; 0.6; 0.75; 0.65; 0.7; 1.8; 1.9; 1.9; 0.85; ...
    0.85; 0.85; 0.85; 0.8; 1.2; 0.9];
equipment.prompt = ("Driver power, kW: "; "Driver power, kW: "; ...
    "Litres/s: "; "kg/h steam: "; "kg/h steam: "; "Diameter, m: "; "Power, kW: "; ...
    "Length, m: "; "Length, m: "; "Height, m: "; "t/h: "; "kg/h: "; "Area, m2"; ...
    "Area, m2: "; "Evap rate, kg/h: "; "Area, m2: "; "Area, m2: "; ...
    "Capacity, m3: "; "area, m2: "; "duty, MW: "; "duty, MW: "; "Flow Litres/s"; ...
    "Power, kW: "; "Power, kW: "; "Capacity, m3: "; "Capacity, m3: "; ...
    "Diameter, m: "; "Diameter, m: "; "Diameter, m: "; "Shell mass, kg: "; ...
    "Shell mass, kg: "; "Shell mass, kg: "; "Shell mass, kg: "; "Volume, m3: "; ...
    "area, m2: "; "area, m2: ");
equipment.s_lower = [5.0; 5.0; 1.0; 5000; 20000; 0.26; 2.0; 10; 10; 10; 30; 200; 11; 3.0; ...
    400; 11; 0.5; 0.4; 10; 0.2; 30; 0.2; 1.0; 100; 100; 10; 0.5; 0.5; 0.5; 160; 160; 120; 120; ...
    10; 10];
equipment.s_upper = [75; 35; 50; 200000; 800000; 0.49; 20; 500; 500; 30; 400; 4000; ...
    180; 20; 4000; 640; 12; 1.4; 180; 60; 120; 126; 2500; 20000; 10000; 4000; 5; 5; 5; 25000];
```

```

50000; 250000; 50000; 100; 1000; 500];

% Calculations:
Ce = -1;
i = 1;
equipment_end = length(equipment.names);

for i = 1:equipment_end
    if equip == equipment.names(i)
        prompt = equipment.prompt(i);
        s_lower = equipment.s_lower(i);
        s_upper = equipment.s_upper(i);
        X = ['Add value between ', num2str(s_lower), ' and ', num2str(s_upper), '.'];
        disp(X)
        user_input = input(prompt);

        if user_input >= s_lower && user_input <= s_upper
            a = equipment.a(i);
            b = equipment.b(i);
            n = equipment.n(i);
            Ce = a + b * user_input.^n;
        else
            msg = 'Error: Value outside acceptable range.';
            error(msg)
        end
    end
end

if Ce == -1
    msg = 'Error: Equipment not identified.';
    error(msg)
end

%% Cost Escalation (all data above given in Jan. 2007):
CE_index_old = 525.4; % [2007]
CE_index_new = 603.1; % [2018]

Ce = Ce * (CE_index_new / CE_index_old);
X = ['Cost of Unit is ', num2str(Ce), ' dollars in 2018.'];
disp(X)

%% Materials Cost Factors (relative to carbon steel)
material.names = ["Carbon steel"; "Aluminum and bronze"; ...
    "Cast steel"; "304 stainless steel"; "316 stainless steel"; ...
    "321 stainless steel"; "Hastelloy C"; "Monel"; "Nickel and Inconel"];
material.fm_vector = [1.0; 1.07; 1.1; 1.3; 1.3; 1.5; 1.55; 1.65; 1.7];
disp(material.names)

fm = -1;
prompt = 'Material of Construction: ';

```

```

user_input = input(prompt, 's');
i = 1;
material_end = length(material.names);

for i = 1:material_end
    if user_input == material.names(i)
        fm = material.fm_vector(i);
        Ce = Ce * fm;
        X = ['Cost of Unit is ', num2str(Ce), ' dollars in 2018.'];
        disp(X)
    end
end

if fm == -1
    msg = 'Error: Material not identified.';
    error(msg)
end

%% Fixed Captial Cost Estimate
CapCost.type = (["Fluids"; 'Fluids-solids'; 'Solids']);
CapCost.f_er = [0.3; 0.5; 0.6];
CapCost.f_p = [0.8; 0.6; 0.2];
CapCost.f_i = [0.3; 0.3; 0.2];
CapCost.f_el = [0.2; 0.2; 0.15];zq
CapCost.f_c = [0.3; 0.3; 0.2];
CapCost.f_s = [0.2; 0.2; 0.1];
CapCost.f_l = [0.1; 0.1; 0.05];

CapCost.ISBL = [3.3; 2.2; 2.5];
CapCost.OS = [0.3; 0.4; 0.4];
CapCost.DE = [0.3; 0.25; 0.2];
CapCost.X = [0.1; 0.1; 0.1];

disp(CapCost.type)
cost = -1;
prompt = 'Process Type: ';
user_input = input(prompt, 's');
i = 1;
CapCost_end = length(CapCost.type);

for i = 1:CapCost_end
    if user_input == CapCost.type(i)
        ISBL = CapCost.ISBL(i);
        OS = CapCost.OS(i);
        DE = CapCost.DE(i);
        X = CapCost.X(i);

        C = Ce * ISBL;
        cost = C * ((1 + OS) * (1 + DE + X)); % Fixed Capital Cost
    end
end
end

```

```
if cost == -1
    msg = 'Error: Process type not identified.';
    error(msg)
end

end
```

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