Globally Optimal Mechanical Design of Sieve Trays in Distillation Columns

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Introduction

- Distillation ⇨ Process of separating components from a mixture to obtain high purity products;
- Traditional design ⇨ by trial and error;
- The literature presents optimization algorithms of distillation columns integrated to a commercial simulator.

Objective

- Develop a trays sizing algorithm minimizing the cost of the distillation column.

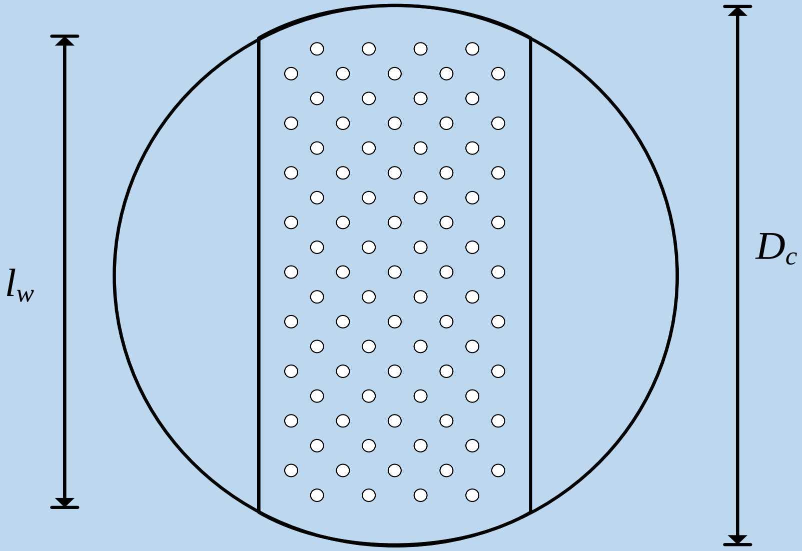
Mathematical formulation

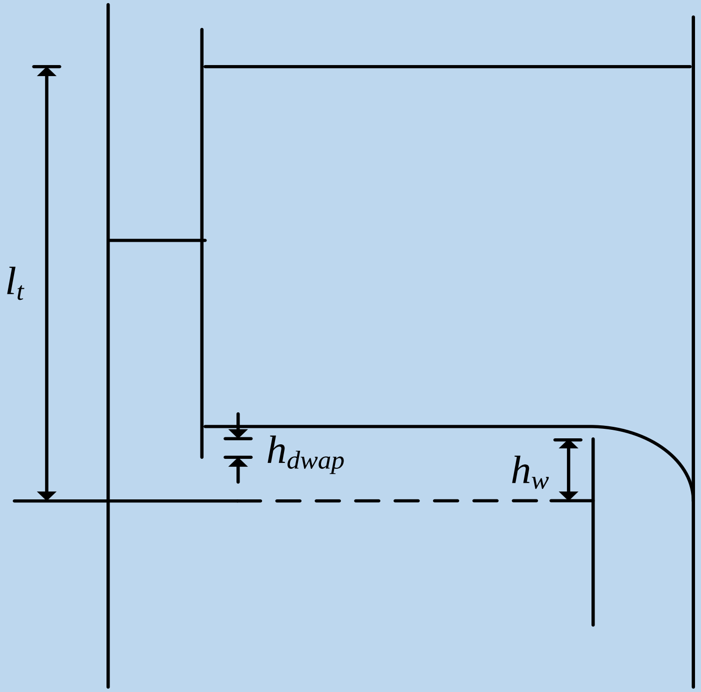
- Operational parameters:
  - V_w ⇨ Vapor mass flow rate
  - L_w ⇨ Liquid mass flow rate
  - ρ_v ⇨ Vapor density
  - ρ_l ⇨ Liquid density
  - ts ⇨ Sufarce tension

- Geometric parameters:
  - ε_t ⇨ Tray thickness
  - N_{eq} ⇨ Number of equilibrium stages
  - Eff ⇨ Column efficiency
  - N_t ⇨ Number of real stages

Mathematical formulation

- Geometric variables:





- d_h ⇨ Hole diameter
- l_p ⇨ Hole pitch
- lay ⇨ Hole layout

Mathematical formulation

- Geometric constraints:
  - Mechanical:

$$l_w < D_c$$

$$l_p > 2d_h$$

$$\frac{d_h}{\varepsilon_t} \geq 1$$

$$D_c > 0.6\,m$$

- Hydraulic:

$$0.05 \leq \frac{A_h}{A_a} \leq 0.16$$

- Fair Correlation:

$$d_h < 0.0065\,m$$

$$h_w < 0.15 l_t$$

$$\frac{A_h}{A_a} \geq 0.10$$

Mathematical formulation

- Operational constraints – Flooding:

$$u_n \leq 0.85 u_f$$

- Flooding velocity:

$$u_f = C_{sb} \sqrt{\frac{\widehat{\rho_l} - \widehat{\rho_v}}{\widehat{\rho_v}}} \left(\frac{\hat{\sigma}}{0.02} \right)^{0.2}$$

- Fair Correlation:

$$C_{sb} = 0.013 + 4.963 \cdot 10^{-4} \, (1000 \, l_t)^{0.835} e^{-1.597 \, F_{LV}{}^{0.827}}$$

Mathematical formulation

- Operational constraints – Entrainment:

$$\psi \leq 0.1$$

➢ Fractional entrainment:

$$\psi = exp\left[-8.6003 + 1.5652 f_{flood} - \left(0.2608 + 1.4962 f_{flood}\right)\ln F_{LV} + \left(-0.1040 + 0.4169 f_{flood} - 0.7227 f_{flood}{}^{2} + 0.2937 f_{flood}{}^{3}\right)(\ln F_{LV})^{2}\right]$$

➢ Percentage flooding :

$$F_{flood} = \frac{u_n}{u_f}$$

➢ Liquid-vapor flow factor :

$$\widehat{F_{LV}} = \frac{\widehat{L_w}}{\widehat{V_w}}\sqrt{\frac{\widehat{\rho_v}}{\widehat{\rho_L}}}$$

Mathematical formulation

- Operational constraints – Weeping:

$$u_h \geq u_{h,min}$$

  - Minimum vapor flow velocity in weep point:

$$u_{h,min} = \frac{K_2 - 0.92(5.4 - 10^3 d_h)}{(\widehat{\rho_v})^{1/2}}$$

Mathematical formulation

- Operational constraints – Downcomer backup:

$$h_b \leq \frac{1}{2}(l_t + h_w)$$

➢ Downcomer backup:

$$h_b = h_w + h_{ow} + h_t + h_{dc}$$

➢ Head loss in the downcomer:

$$h_{dc} = 166 \cdot 10^{-3} \left(\frac{\widehat{L_{l,dc}}}{\widehat{\rho}_l A_{ap}} \right)$$

Mathematical formulation

- Operational constraints – Downcomer backup:
  - Total plate pressure drop:

$$h_t = h_w + h_{ow} + h_d + \widehat{h_r}$$

  - Dry plate drop and residual loss:

$$h_d = 51 \cdot 10^{-3} \left(\frac{u_h}{C_0}\right)^2 \frac{\widehat{\rho_v}}{\widehat{\rho_l}} \qquad \widehat{h_r} = \frac{12.5}{\widehat{\rho_l}}$$

  - Height of the liquid crest over the weir:

$$h_{ow} = 750 \cdot 10^{-3} \left[\frac{\widehat{L_w}}{\widehat{\rho_l} l_w}\right]^{2/3}$$

Mathematical formulation

- Operational constraints – Residence time:

$$t_r = \frac{A_{dc} h_b \widehat{\rho}_l}{\widehat{L}_l} > 3s$$

Mathematical formulation

- Minimizing the cost:

$$Min\ C_{total} = (130 + 440{D_c}^{1.8})N_t + 11600 + 34{W_{shell}}^{0.85}$$

- Weight of the column shell:

$$W_{shell} = Cw\ \pi\ \rho_{shell}\ D_m(H_c + 0.8D_m)t_{wall}$$

- Wall thickness:

$$t_{wall} = \frac{P_c D_c}{2\ S\ E\ - 1.2P_c}$$

Results

- Case study:
  - Feed: aqueous waste – 10% in mol of acetone
  - Top: 95% in mol of acetone
  - Bottom: 1 % in mol of acetone
- Geometric parameters:
  - Number of equilibrium stages : 10
  - Column efficiency : 60%
  - Number of real stages: 15

Parameters of column	Value
Thickness of trays from carbon steel – ε_t	0.0034 m
Specific mass of carbon steel – ρ_w	7900 kg/m³
Maximum allowable stress of carbon steel – S	$8.894 \cdot 10^7$ N/m²

- **Results** – Commercial alternatives from the geometric variables:

Variables	Number of components	Range (m)	Minimum (m)	Maximum (m)
D_c	29	0.1524	0.6096	4.8768
d_h	6	-	0.0035	0.006
h_{dwap}	6	0.001	0.005	0.01
h_w	9	0.00635	0.0381	0.0889
l_t	6	-	0.1524	0.9144
l_w	19	0.2032	0.4064	4.2164
l_p	6	0.003	0.009	0.024
lay	2	-	square	triangular

- **Results** – Operational parameters :

Parameters/ Tray	1	2	3	4	5	6	7	8	9
L_w (kg/s)	0.82	0.80	0.78	0.76	0.72	0.66	0.51	3.12	2.78
V_w (kg/s)	1.50	1.48	1.46	1.43	1.40	1.34	1.18	1.02	0.68
ρ_l (kg/m³)	753.76	754.64	755.64	756.92	758.84	762.57	776.27	873.01	900.73
ρ_v (kg/m³)	2.10	2.09	2.07	2.04	2.01	1.95	1.78	1.61	1.02
ts (N/m)	22.28	23.20	24.21	25.45	27.21	30.28	38.60	59.14	60.79

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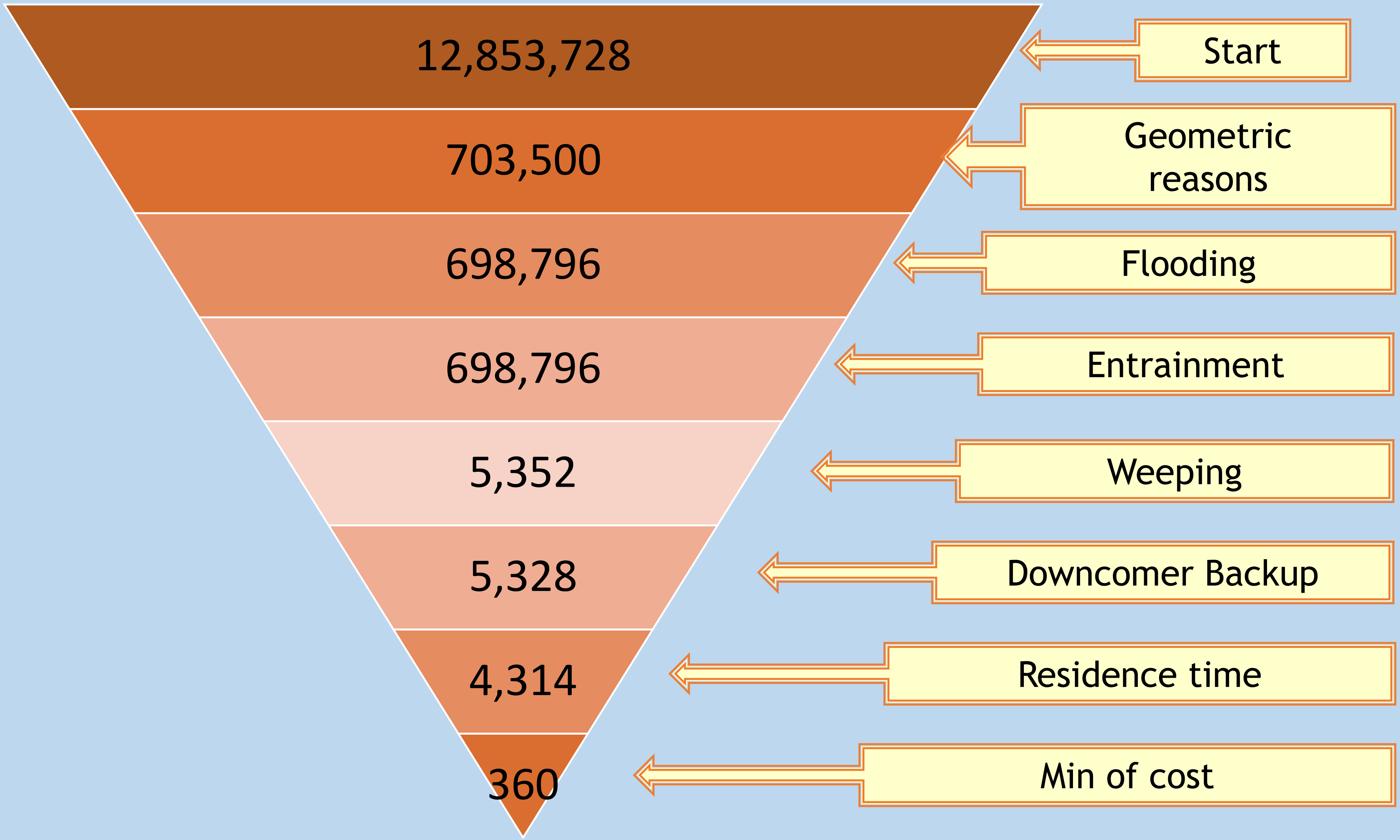

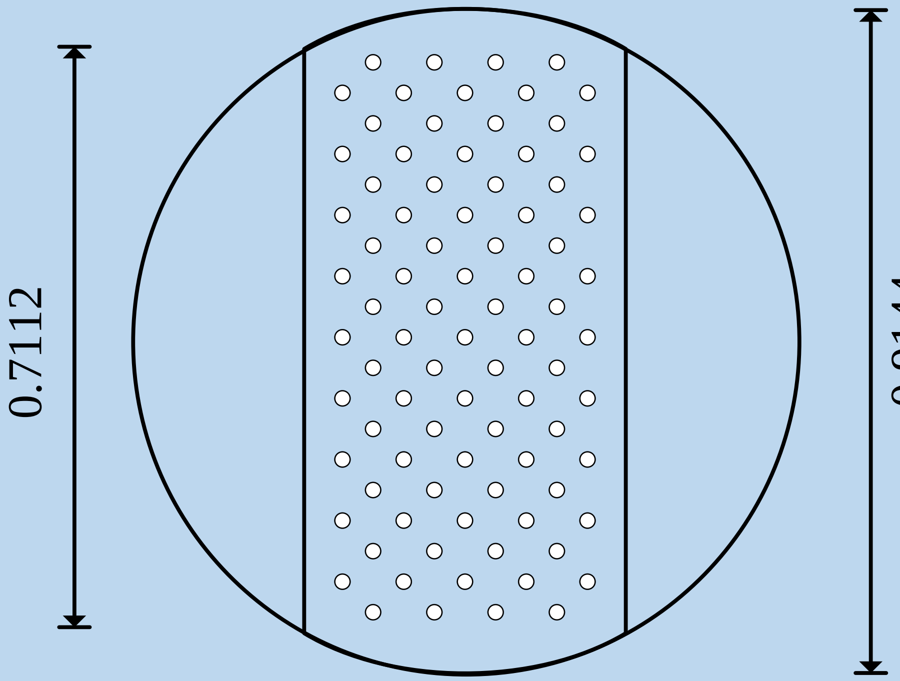

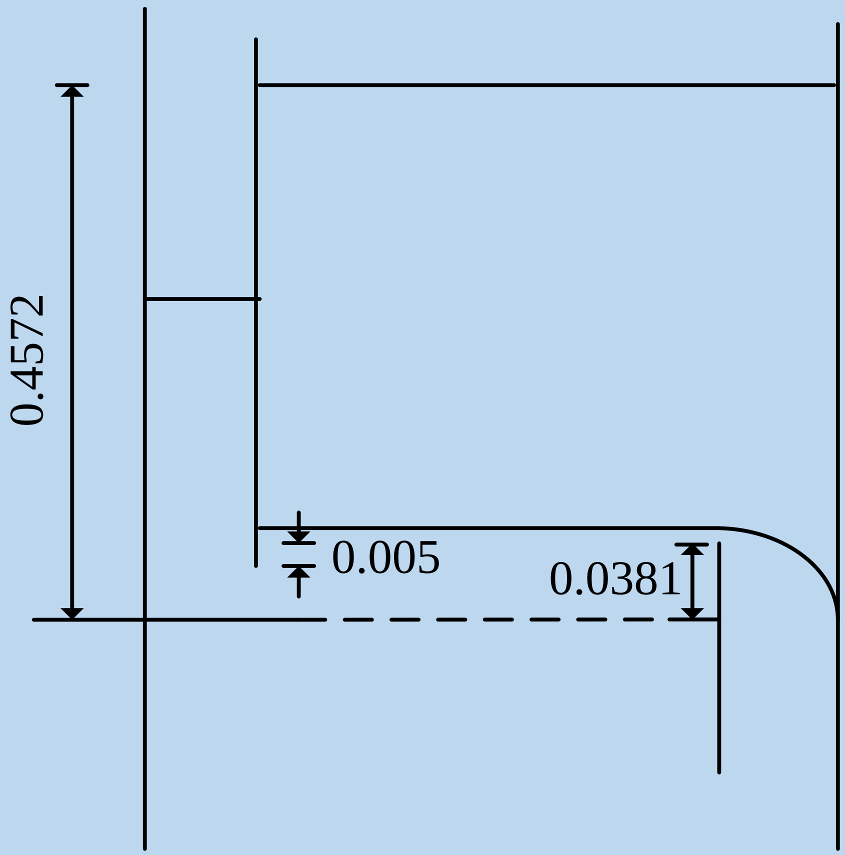

- d_h ⇨ 0.0035 m
- l_p ⇨ 0.009 m
- lay ⇨ square
- C_{total} ⇨ 31,193.85 $

Conclusion

- A Set Trimming procedure was implemented for the design of sieve tray columns.
- We found several alternative optima featuring the same cost.
- Future work involves advance sorting based on pressure drop.