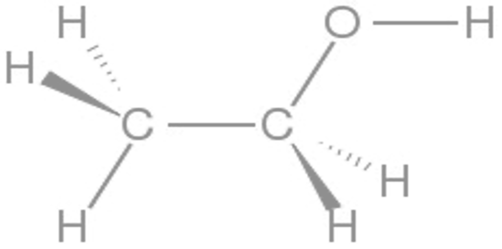

Design and Economics of a Bioethanol Plant

CHE 432 Group 22

Nick Seta

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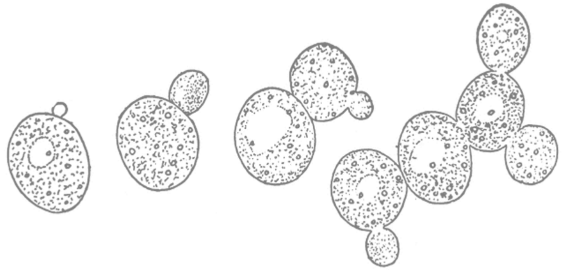


Bioethanol Plant Design Overview

Introduction & Design Overview

Fermentation

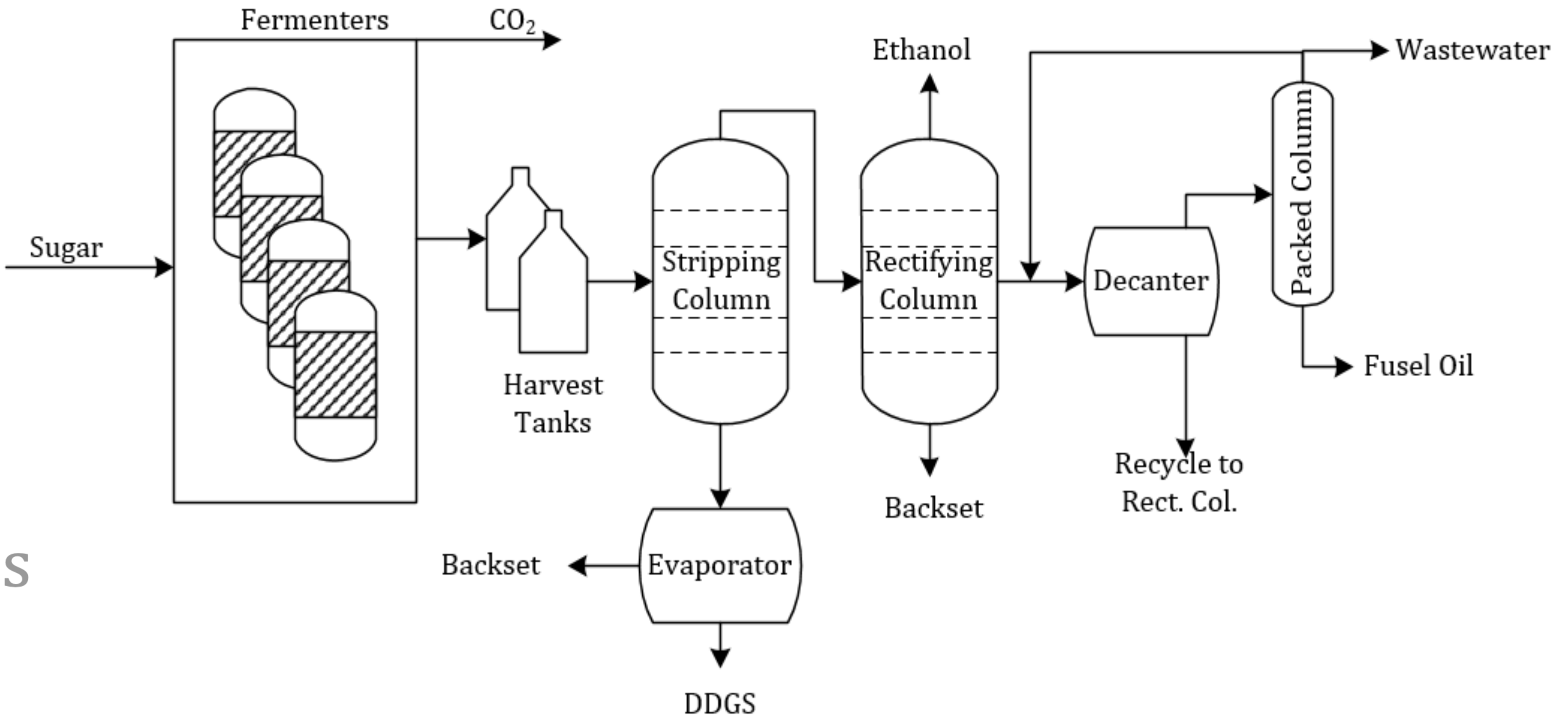
Ethanol Recovery

Fusel Recovery

Process Economics

Process Hazard Analysis

Conclusions



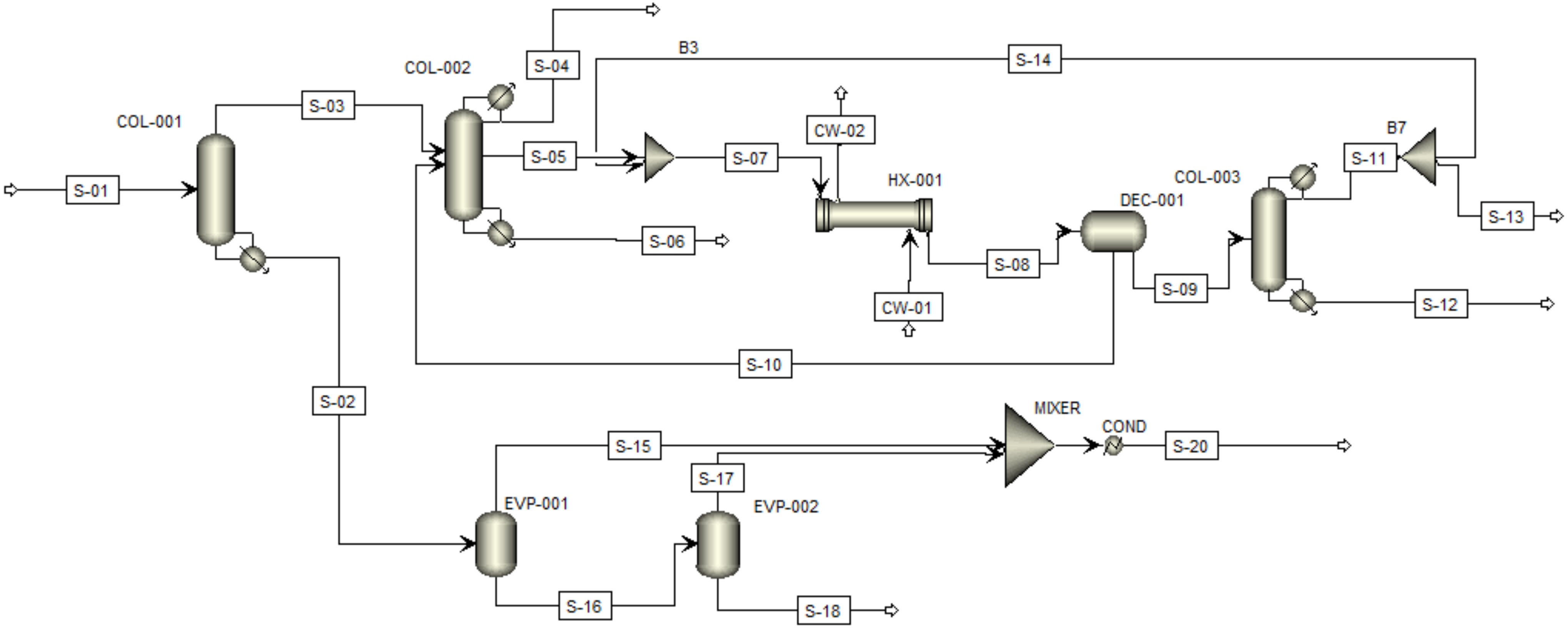
Introduction

- A bioethanol plant was designed to produce $75*10^6$ gal/yr of 90 vol% ethanol
  - Simultaneous saccharifcation and fermentation followed by ethanol recovery was used
  - A flow sheet, mass & energy balances, and equipment specifications were developed
- A fusel oil recovery system was designed and economic feasibility was evaluated
  - Process economics were evaluated with and without the recovery system

Process Simulation

- Continuous portions of process modeled
  - Ethanol recovery, fusel oil recovery, waste processing

- Thermodynamic model: **UNIQ-RK**



Fermentation: Overview

- **Assumptions[1]:**
  - Conversion of 0.9
  - 5 gallon fusel oil/1000 gallon ethanol
  - Maximum survivable alcohol concentration – 0.16 vol/vol
  - Negligible mass contribution from yeast and enzyme

$$Fermentation\ Time = \frac{Concentration}{Productivity} = \frac{153\ g\ L^{-1}}{3\ g\ L^{-1} hr^{-1}} \sim 50\ hrs$$

$$Total\ Time = 50\ hr + 5\ hr\ (processing) + 5\ hr\ (cleaning) = 60\ hrs$$

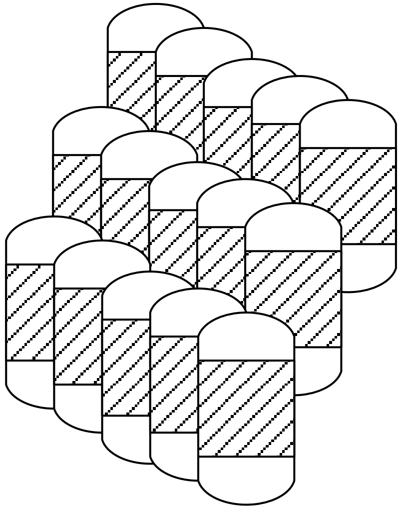
$$Time\ Unitl\ Empty = \frac{Tank\ Size}{Volume\ Flow} = \frac{1000\ m^3}{200\ m^3 hr^{-1}} = 5\ hrs$$

$$Number\ of\ Banks = \frac{Total\ Time}{Time\ Until\ Empty} = \frac{60\ hrs}{5\ hrs} = 12\ banks$$

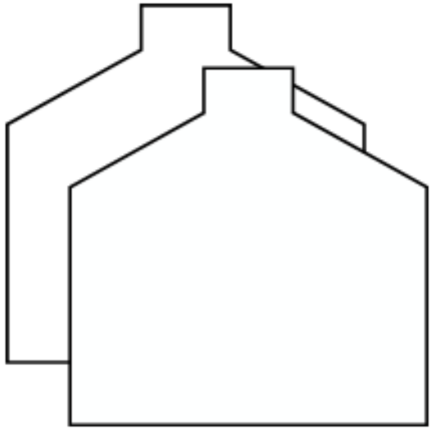
[#]: Kosaric, N., Vardar-Sukan, F., Pieper, H. J. *The Biotechnology of Ethanol: Classical and Future Applications.* 2001 Wiley-VCH. Book.

Fermentation: Equipment Design

12 banks
- 5 fermenters
- Carbon Steel
- 200 m^3 each
- Staggered 5 hours



50 hour fermentation



2 Harvest Tanks
- 1000 m^3 each
- Carbon Steel

Fermenter Volume:	200 m^3
No. of Vessels	60
Material of Construction:	Carbon Steel
Purchase Cost:	$ 3,223,506

Harvest Tank Volume:	1000 m^3
No. of Vessels	2
Material of Construction:	Carbon Steel
Purchase Cost:	$ 229,506

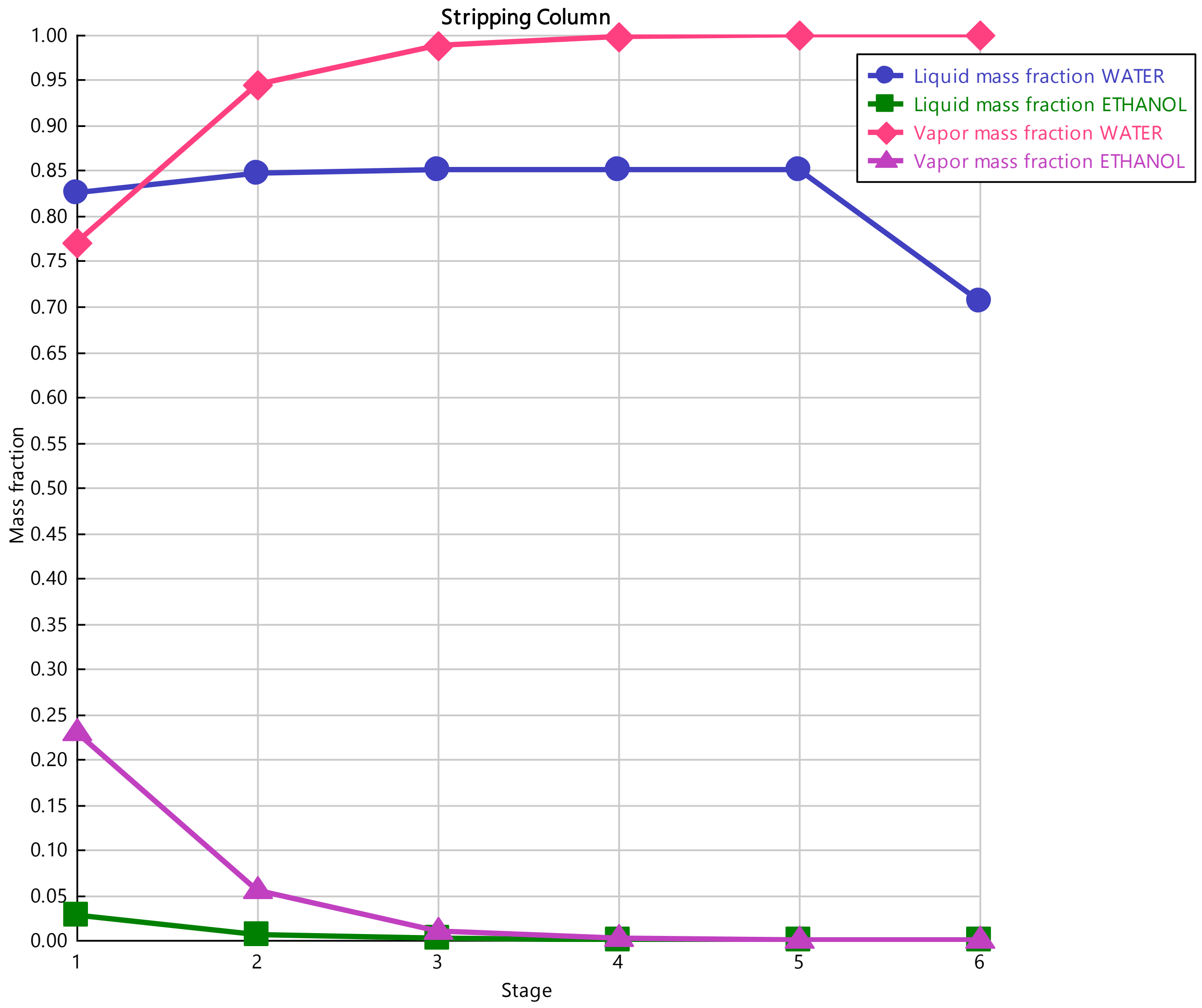
[#]: Kosaric, N., Vardar-Sukan, F., Pieper, H. J. *The Biotechnology of Ethanol: Classical and Future Applications.* 2001 Wiley-VCH. Book.

Fermentation: Operating Schedule

Time	*Bank 1*	*Bank 2*	*Bank 3*	*Bank 4*	*Bank 5*	*Bank 6*	*Bank 7*	*Bank 8*	*Bank 9*	*Bank 10*	*Bank 11*	*Bank 12*
0 hrs	Flowing	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Cleaning
5 hrs	Cleaning	Flowing	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment
10 hrs	Ferment	Cleaning	Flowing	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment
15 hrs	Ferment	Ferment	Cleaning	Flowing	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment
20 hrs	Ferment	Ferment	Ferment	Cleaning	Flowing	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment
25 hrs	Ferment	Ferment	Ferment	Ferment	Cleaning	Flowing	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment
30 hrs	Ferment	Ferment	Ferment	Ferment	Ferment	Cleaning	Flowing	Ferment	Ferment	Ferment	Ferment	Ferment
35 hrs	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Cleaning	Flowing	Ferment	Ferment	Ferment	Ferment
40 hrs	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Cleaning	Flowing	Ferment	Ferment	Ferment
45 hrs	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Cleaning	Flowing	Ferment	Ferment
50 hrs	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Cleaning	Flowing	Ferment
55 hrs	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Cleaning	Flowing
60 hrs	Flowing	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Ferment	Cleaning

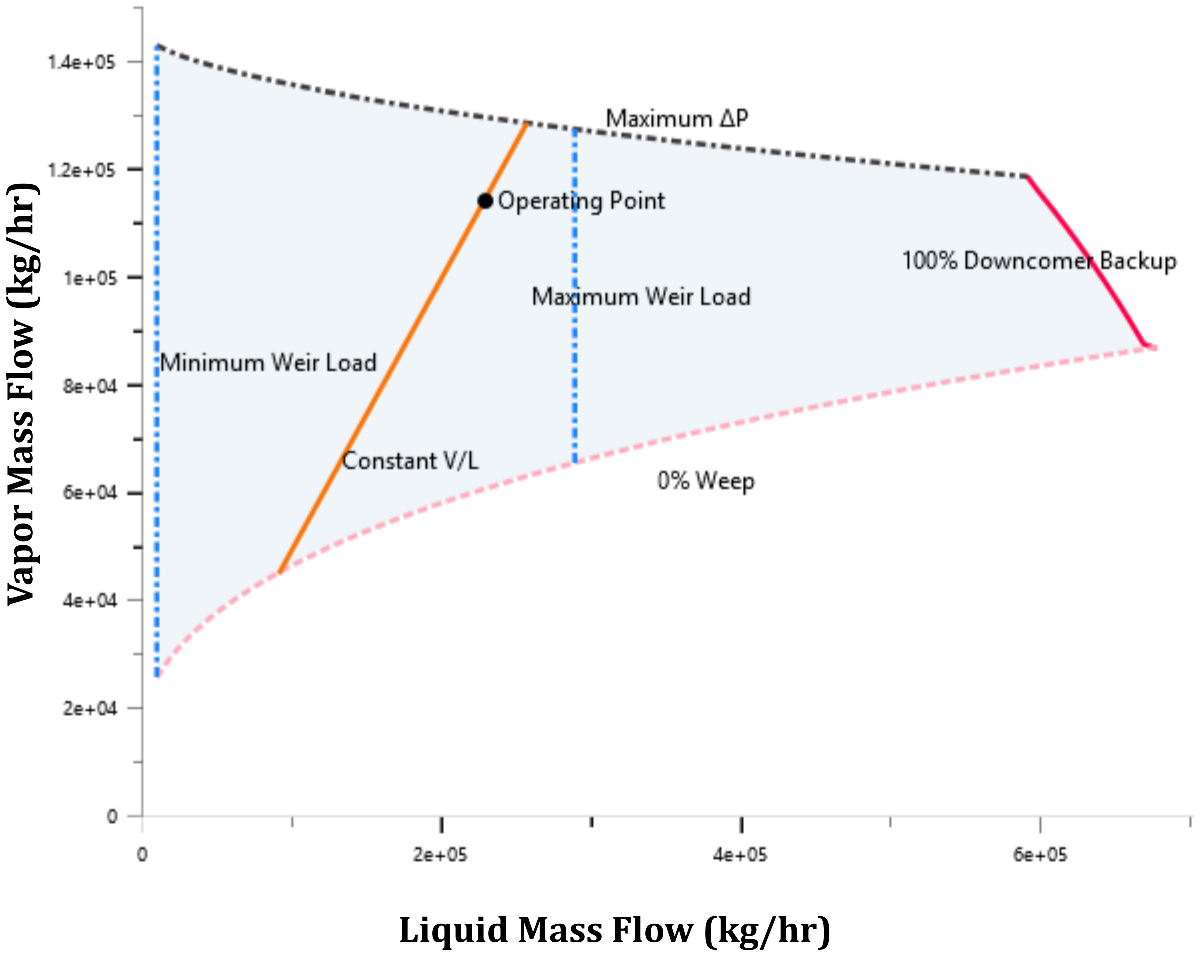
Ethanol Recovery: Stripping Column

- Column Specifications
  - Bottoms flowrate based on 70 wt-%. liquid to 30 wt-% solids
- No condenser is used to save energy
  - No reflux possible
- Amount of Stages:
  - 3 plus a reboiler

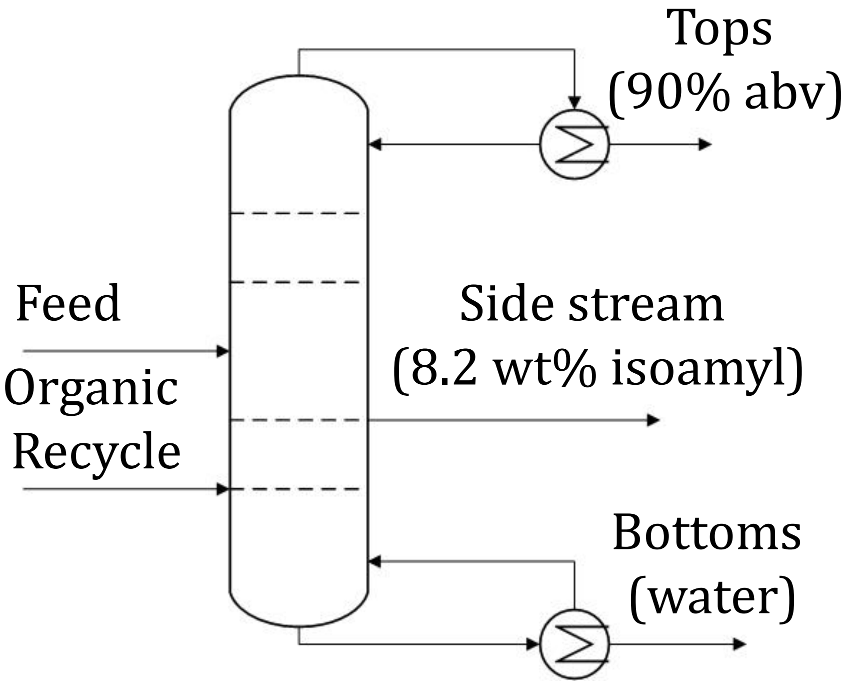


Ethanol Recovery: Stripping Column

Operating Pressure (psig):	10
Reflux Ratio	0
Total Number of Stages	3 plus a reboiler
Tray Spacing (m)	0.9
Diameter(m)	3.1
Percent Flooding	80%
Tray Type	Nutter-BDP
Total Height(m)	7
Space above top tray(m)	3
Space bellow bottom tray(m)	1.2
Material of Construction	Stainless Steel
Installed Purchase Cost w/ Auxiliaries	$ 580,000.00



Ethanol Recovery: Rectifying Column

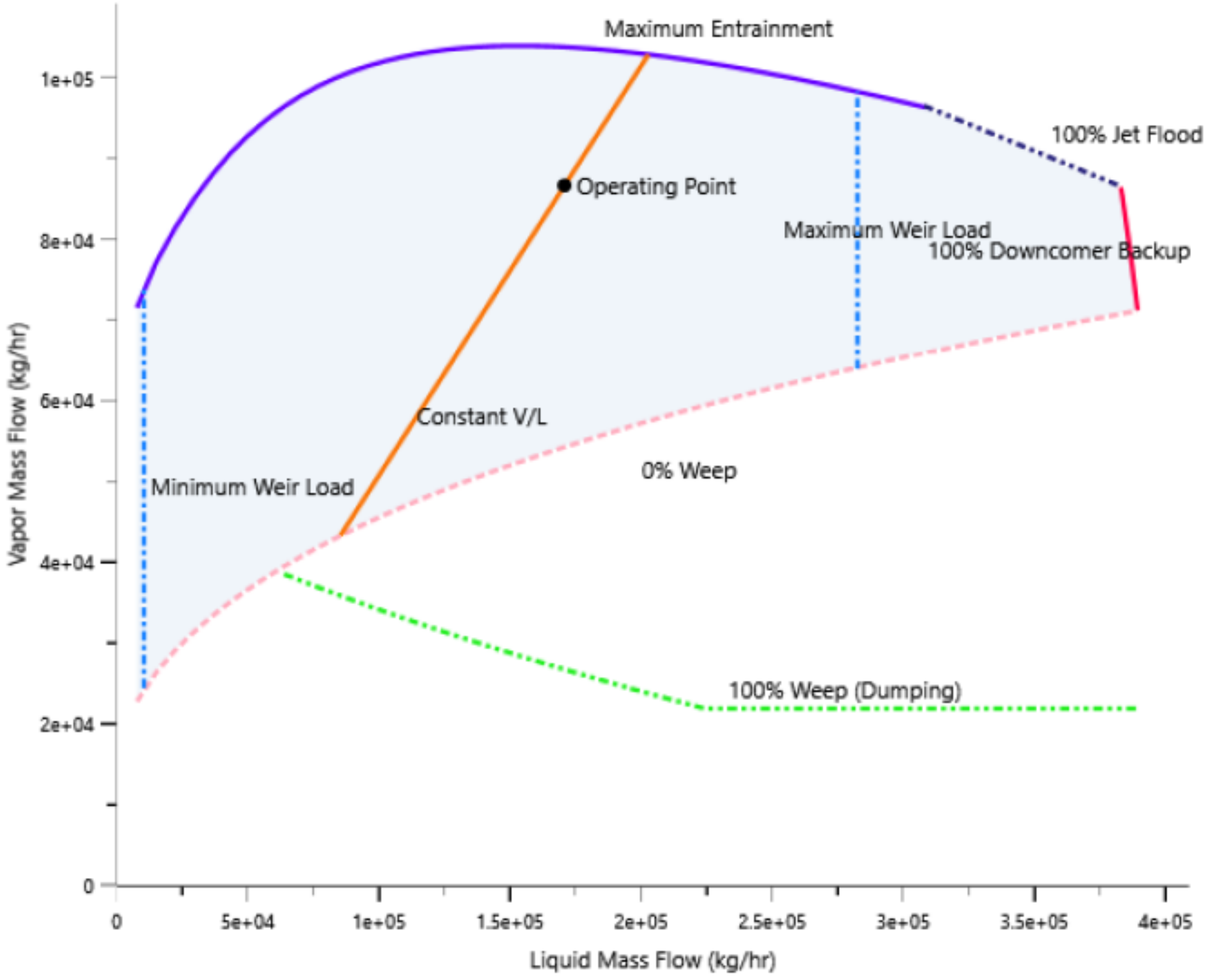


Total Height (m):	19
Space above 1st Tray (m):	3.0
Space below 25th Tray (m):	1.2
Number of Sections:	3
Diameters (m):	3.9, 3.9, 3.5
Total Number of Stages:	26
Reflux Ratio (mass):	3.0
Operating Pressure (psig) :	10
Murphree Stage Efficiency:	70%
Material of Construction:	316 SS
Purchase Cost w/ Auxiliaries:	$ 520,000

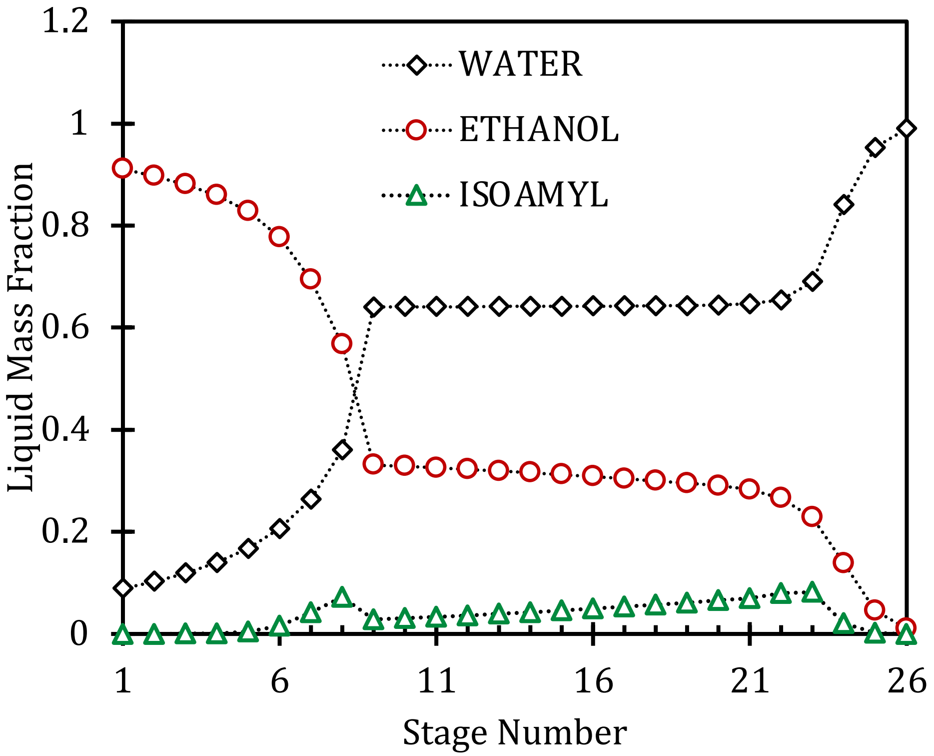
- Hydraulic plots generated for each tray verified functional operation
  - i.e. No weeping or entrainment
- Side stream taken above Tray 24 where isoamyl was most concentrated
  - Heterogenous azeotrope of isoamyl alcohol and water at 95.1 °C [1]
- Organic stream from decanter recycled as feed stream underneath intermediate take-off

[1]dx.doi.org/10.1021/ie300665z, Ferreira et al., 2013

Ethanol Recovery: Rectifying Column

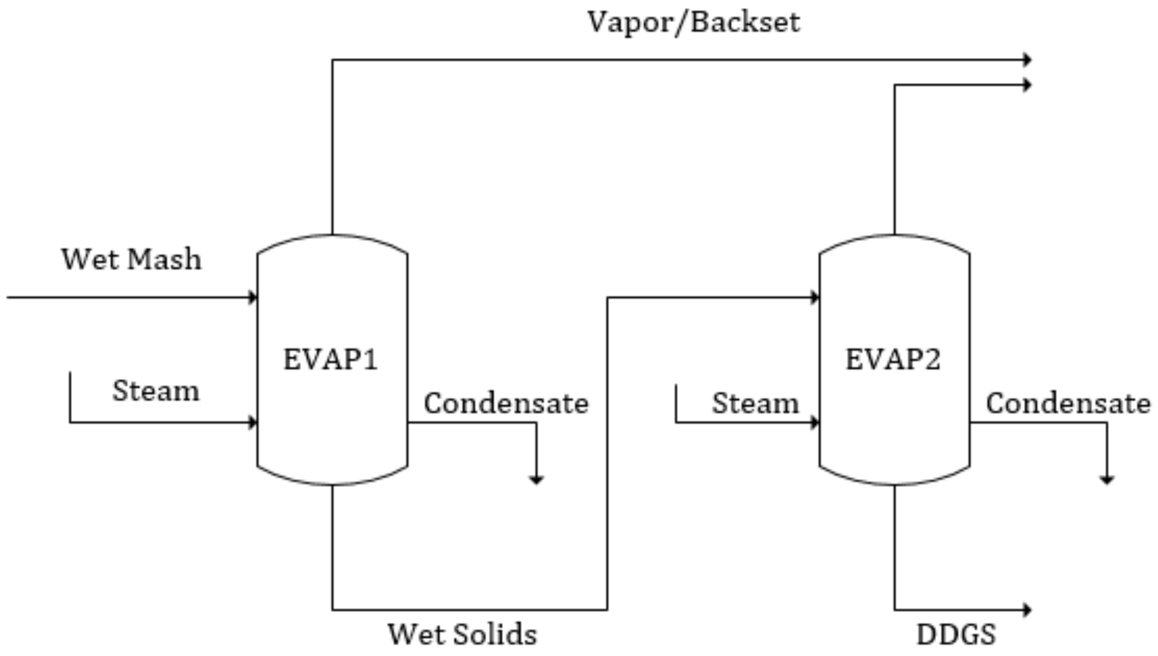


Example hydraulic plot



Liquid composition profile

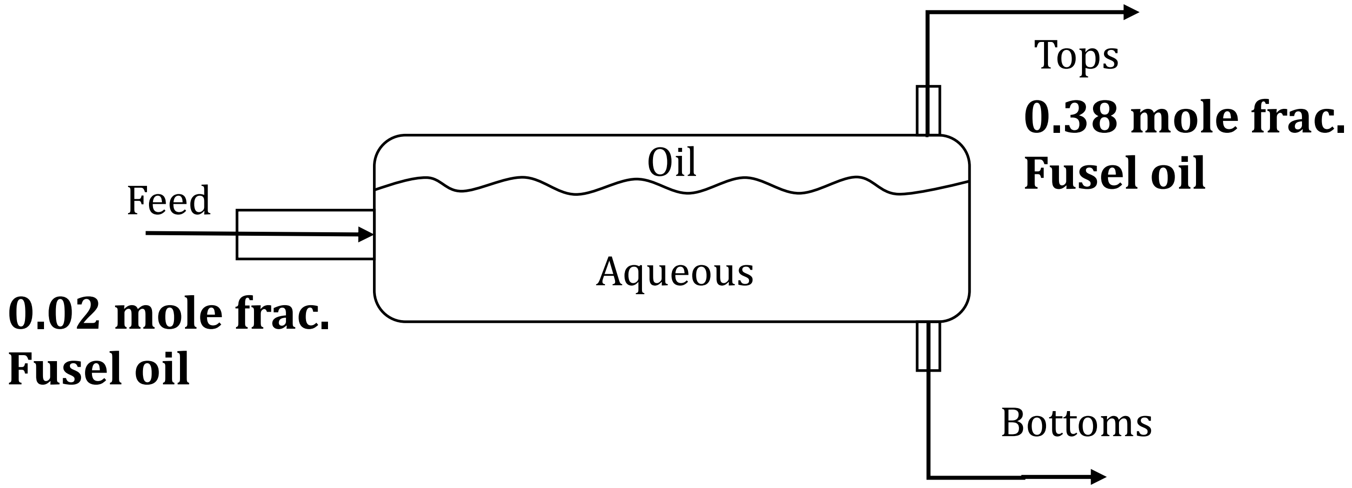
Ethanol Recovery: DDGS Product



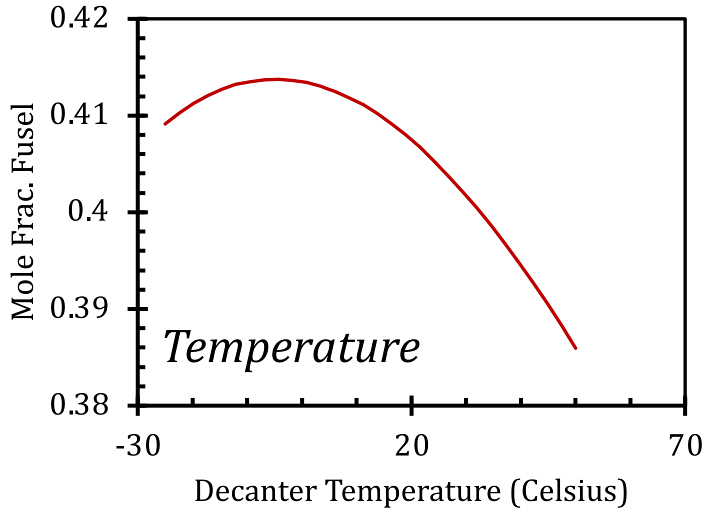
Heat Transfer:	22500 kW
Overall heat transfer coefficient:	680 W^2/m^2K
Heat Transfer Area:	750 m^2
Log Mean Temperature Difference:	44.1 K
Moisture Content of Wet Mash:	70 mass-%
Moisture Content of Wet Solids:	50 mass-%
Moisture Content of DDGS:	15 mass-%
Material of Construction:	304 SS
Purchase Cost:	$1,173,474

- Two single-effect evaporators in series, slight differences between each
- Optimized in ASPEN to determine minimum heat duty for desired DDGS moisture content
- DDGS waste is sold to respective market

Fusel Recovery: Decanter

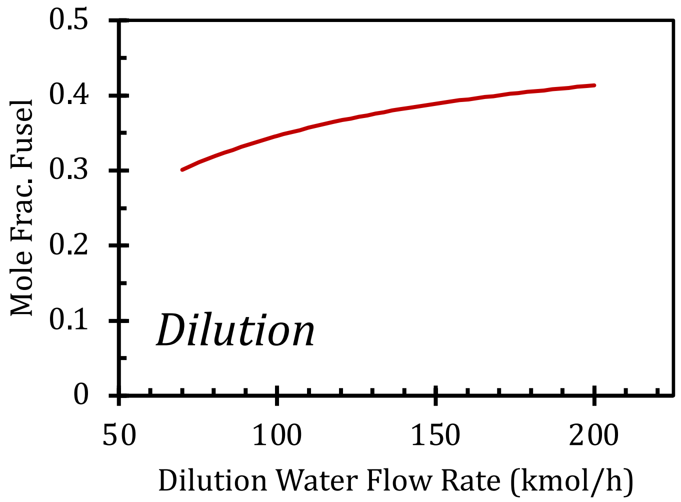


Key operating Parameters

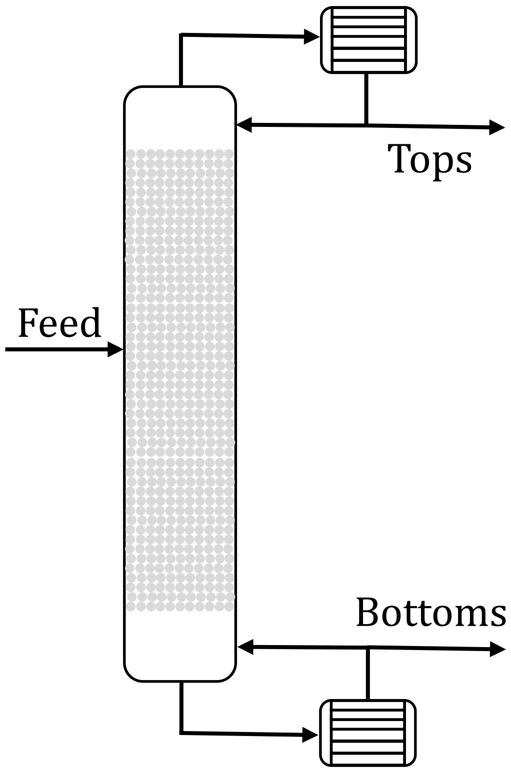


- **88%** fusel oil recovered in tops of decanter
  - Bottoms recycled to rectifying column
- Costed as a horizontal vessel

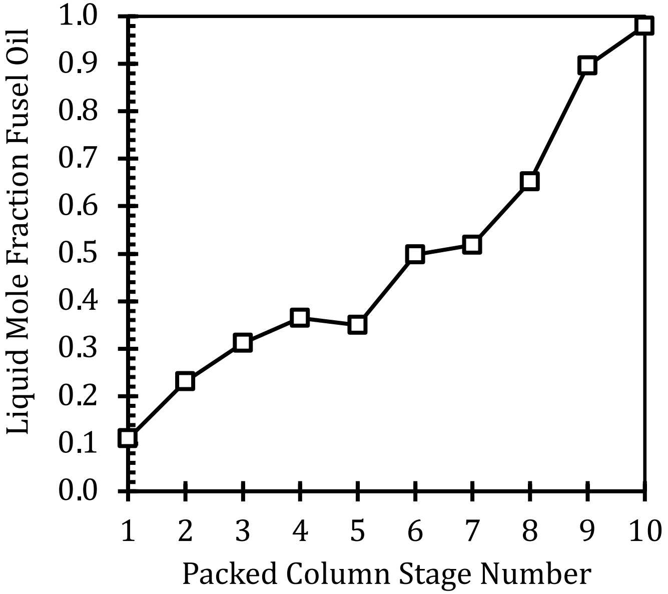
Length:	8.0 m
Diameter:	0.5 m
Volume:	1.57 m^3
Residence time:	43 min
Material of Construction	316 SS
Purchase Cost:	$16,491



Fusel Recovery: Packed Column



- Fusel product is bottoms of packed column:
  - **97% recovery**
  - **93 mole-% Fusel oil**
  - **98 mass-% Fusel oil**
- Costed with column and packing price
- Tops is recycled as decanter diluent



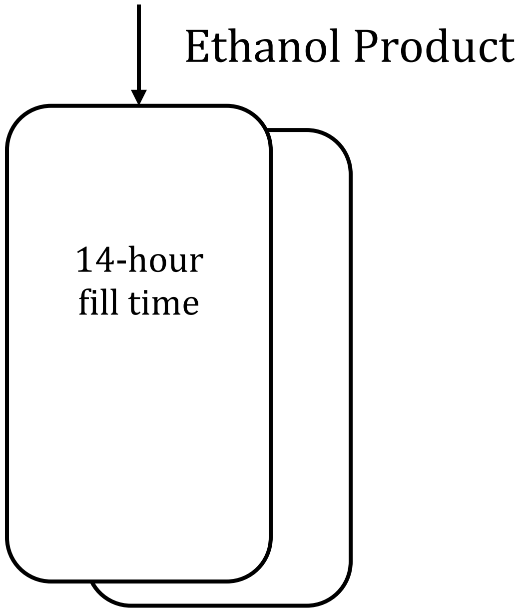
Height:	6.1 m
Diameter:	0.5 m
No. of Stages:	10
Feed Stage:	6
Packing Type:	1/2” Raschig Rings
HETP:	0.75 ft
Material of Construction:	316 SS
Purchase Cost:	$ 63,705

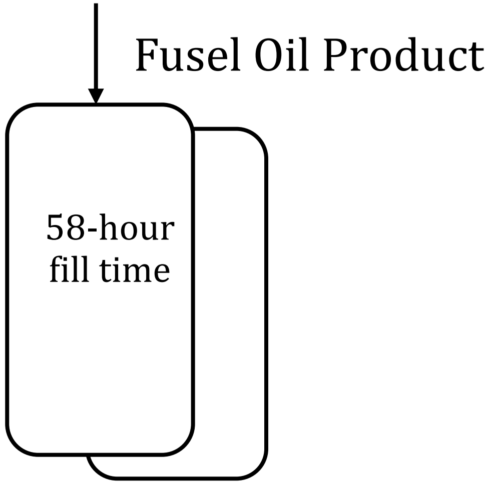
Product Storage

- Two 500 m^3 storage tanks for ethanol product
  - Allows a **14-hour** buffer before one tank is full
  - Shipping may not always be reliable (second tank)
  - Allow multiple truck filling stations

- Two 10 m^3 storage tanks for fusel oil product
  - Allows a **58-hour** buffer time before tank is full
  - Second tank for shipping issues/cleaning

	Ethanol	**Fusel oil**
Volume:	500	10
Design Pressure:	1 atm	1 atm
Material of Construction:	316 SS	316 SS
Purchase Cost (2 tanks):	$ 339,373	$ 108,306





Total Capital investment

- Factorial method of cost estimation to relate equipment cost to total capital investment for the plant[#]
- Solids/Liquid Processing Plant:
  - Total **"Lang Factor" of 4.27**
- **$28,000,000** capital investment for ethanol production and fusel recovery

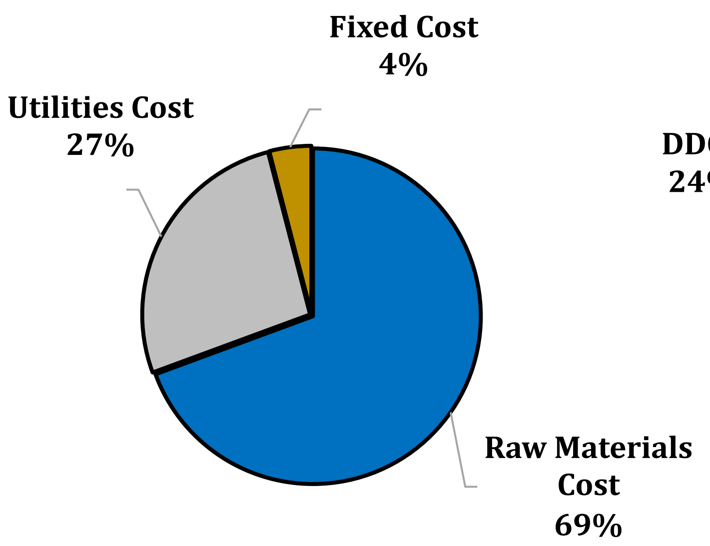
Ethanol Plant			Fusel Recovery Plant Addon		
Equipment Purchase Cost:	$	6,309,358	***Equipment Purchase Cost:***	$	205,618
Installation Cost:	$	2,586,837	***Installation Cost:***	$	84,303
Piping Cost:	$	2,302,916	***Piping Cost:***	$	75,051
Electrical Costs:	$	788,670	***Electrical Costs:***	$	25,702
Instrument Costs:	$	820,217	***Instrument Costs:***	$	26,730
Building and Service Cost:	$	1,924,354	***Building and Service Cost:***	$	62,713
Excavation and site prep cost:	$	946,404	***Excavation and site prep cost:***	$	30,843
Auxiliaries cost:	$	3,249,319	***Auxiliaries cost:***	$	105,893
Total Physical Plant Investment:	$	18,928,074	***Total Physical Plant Investment:***	$	616,854
Field Expense:	$	2,460,650	***Field Expense:***	$	80,191
Engineering Cost:	$	2,460,650	***Engineering Cost:***	$	80,191
Direct Plant costs:	$	4,921,299	***Direct Plant costs:***	$	160,382
Contractor's fees:	$	820,217	***Contractor's fees:***	$	26,730
Contingency cost:	$	2,460,650	***Contingency cost:***	$	80,191
One-time labor fees:	$	3,280,866	***One-time labor fees:***	$	106,921
Total Capital Cost:	$	27,130,239	***Total Capital Cost:***	$	884,157

[#] Perry, R. H. *Perry's Chemical Engineers' Handbook.* Seventh Edition. McGraw Hill. 1997. Book.

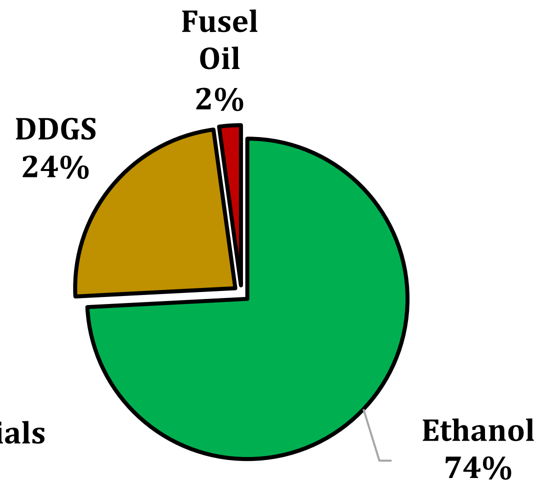
Ethanol Plant Economics

	Ethanol Production Plant	With Fusel Recovery Plant Add-on
Revenue (USD/year):	160,000,000	170,000,000
Manufacturing Cost (USD/year):	(190,000,000)	(190,000,000)
Net Profit (USD/Gal Ethanol):	(0.34)	(0.31)
NPW (10 years):	(250,000,000)	(240,000,000)

- Primary expense is corn: **$ 3.56/Bushel**
- Fusel oil has a higher return than ethanol
  - **$10.68/gallon** Fusel Oil
  - **$1.64/gallon** Ethanol
- Fusel recovery add-on pays for investment in: **3 months**
- Recovering DDGS is expensive but valuable revenue: **$ 135/ton**[#]



Cost of Ethanol Production



Plant Revenue

[3]: U.S. Grains Council. *Ethanol Market and Pricing Data.* November 2017
[2]: ICIS. *Chemical Prices-I Source: CMR.* September 2000
[#]: The Progressive Farmer. *DDG Prices Higher.* November 2018

Hazards Analysis

- Milling introduces risk for dust explosions
  - $T_{byproducts} < 240\ °C$[#]
  - Proper cooling and ventilation

- Alcohols are highly flammable & carcinogenic at high levels
  - Process streams will be kept out of flammability limits
  - Proper PPE when handling alcohols

- Fermentation involves the processing of biological material
  - Implement pressure relief system in fermentation tanks
  - Ventilation in fermentation area to avoid CO_2 over exposure
    - CO_2 evolved could potentially be ran through a gas scrubber

[#] https://onlinelibrary.wiley.com/doi/epdf/10.1002/fam.810120306, Y. Miron et al., 1988

Recommendations and Conclusions

- For an existing plant:
  - Fusel recovery is a good investment
- Construction of a new plant does not make sense
  - Net loss of 31 cents per gallon of ethanol produced
- Carbon dioxide scrubber
- Alternative starting materials: Waste streams from other plants
- Alternative microorganism: *Zymomonas mobilis*- high productivity
- Alternative bioreactor: CSTR – 6 g $L^{-1}h^{-1}$

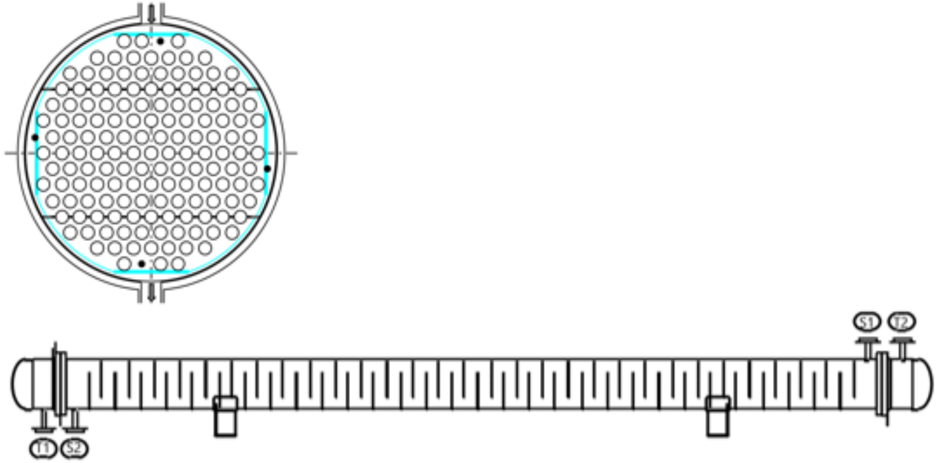
Questions?

Reference Slides

Fusel Recovery: Heat Exchanger

- Decanter feed cooled from 80°C to 5°C
- Aspen EDR Console used to identify optimum design
- Coolant: 50% ethylene glycol and water at -20°C
    - Required flow rate: 10.6 gpm
- Costed based on heat exchange area for fixed head exchangers

Length:	6.0 m
Shell OD:	0.36 m
Tube OD:	0.75 in
No. of Tubes:	149
No. of Baffles	60
No. of Shell/Tube Passes	1/1
Heat Exchange Area	50.1 m^2
Material of Construction	316 SS
Purchase Cost:	$17,116



Hazards Analysis - Materials

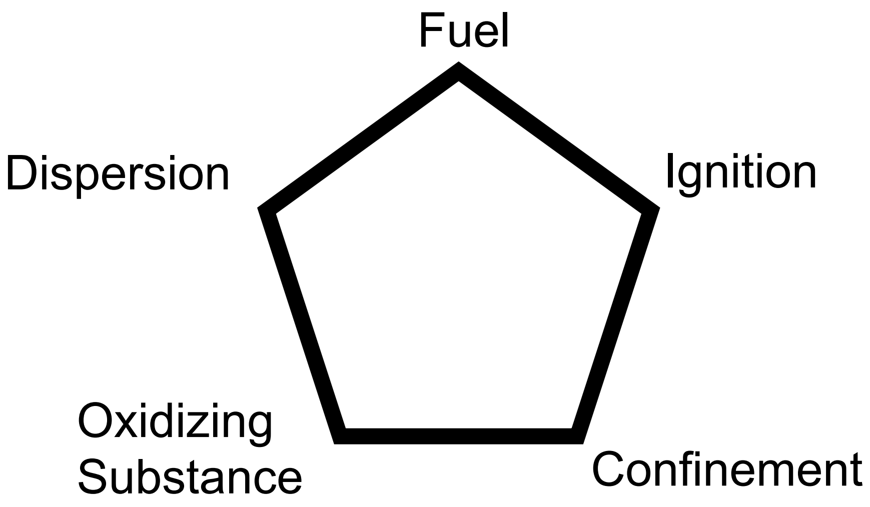
- Fermentation involves the processing of biological and organic material
  - Process is operated at $P = P_{atm}$ and $T < 100\ °C$
  - Biological material impose risk of biological hazards

Hazards Analysis - Milling

- Milling process introduces a dust which can lead to an explosion

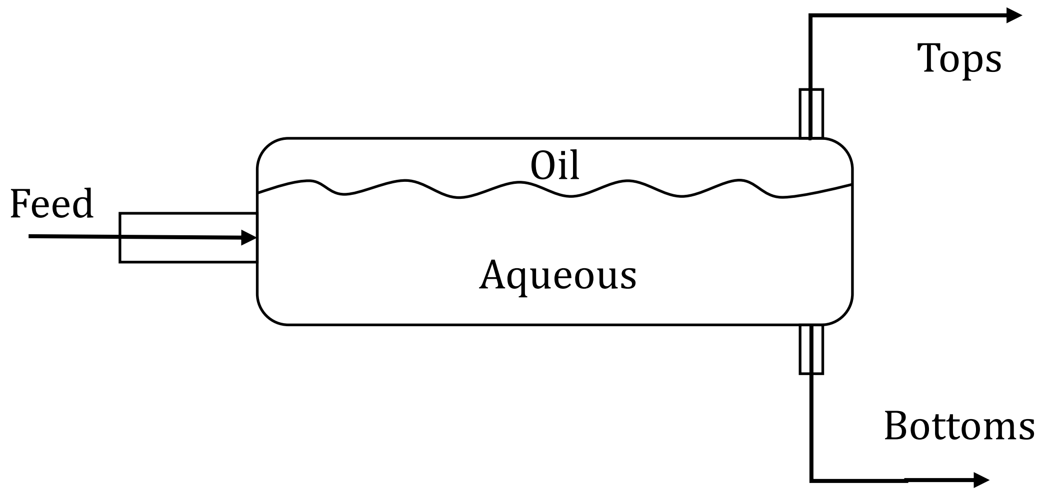
- Combustible dust pentagon warrants the following for an explosion to occur:
  - Ignition = electrical & overheating
  - Fuel = corn milling byproducts
  - Confinement = any closed off area
  - Dispersion = any scattering of byproducts
  - Oxidizing Substance= air

- $T_{byproducts} < 240\ °C$[1]



[1] https://onlinelibrary.wiley.com/doi/epdf/10.1002/fam.810120306, Y. Miron et al., 1988

Fusel Recovery: Decanter



- 88% fusel oil recovered in tops of decanter
  - Bottoms recycled to rectifying column
- Mole fraction of fusel oil increased (0.02 → 0.38)
- Costed as a horizontal vessel

Feed		
Water	71.9	kmol/hr
Ethanol	6.9	kmol/hr
Fusel Oil	1.7	kmol/hr
Total	80.5	kmol/hr

Bottoms		
Water	70.6	kmol/hr
Ethanol	5.8	kmol/hr
Fusel Oil	0.2	kmol/hr
Total	76.6	kmol/hr

Tops		
Water	1.3	kmol/hr
Ethanol	1.1	kmol/hr
Fusel Oil	1.5	kmol/hr
Total	3.9	kmol/hr

Length:	8.0 m
Diameter:	0.5 m
Volume:	1.57 m^3
Residence time:	43 min
Material of Construction	316 SS
Purchase Cost:	$16,491

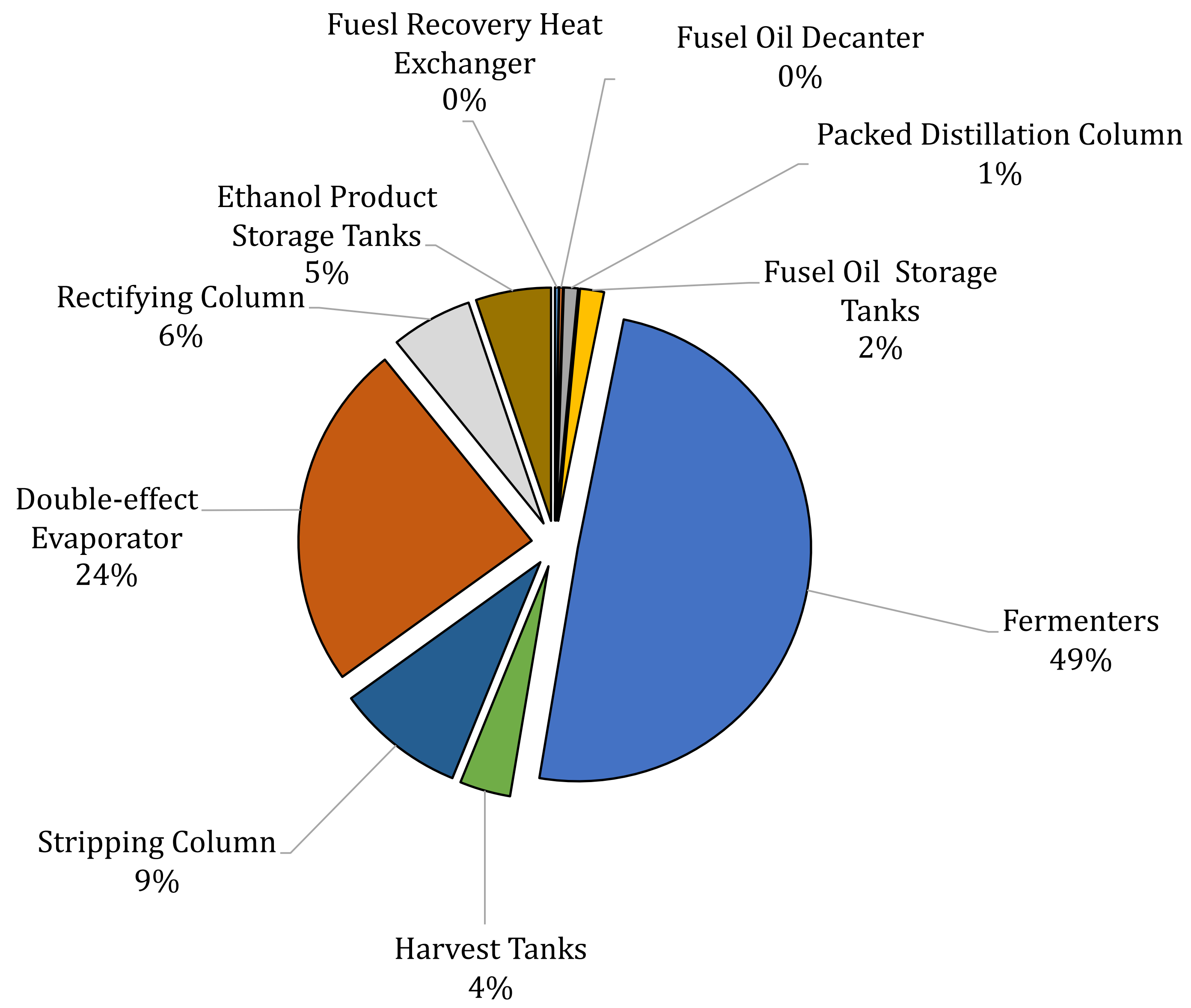
Major Equipment Cost and Pricing

Fusel Recovery Plant Addon

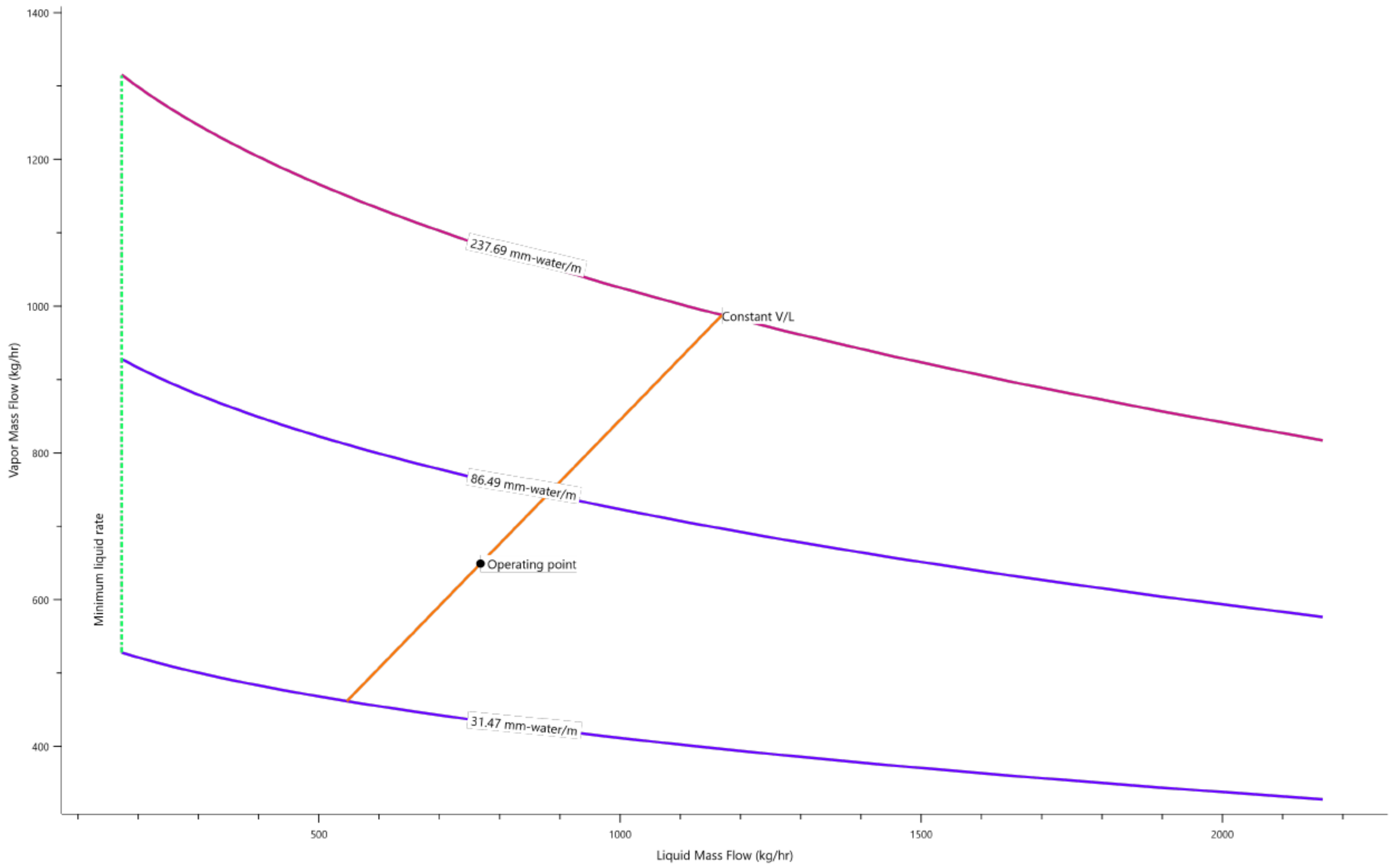
Major Equipment	***Purchase Cost***
Fusel Take-off stream heat exchanger	$ 17,116
Fusel Oil Decanter	$ 16,491
Packed Distillation Column	$ 63,705
Fusel Oil Product Storage Tank	$ 108,306
Total Major Equipment Cost:	$ 205,618

Ethanol Production Plant

Major Equipment	***Purchase Cost***
Fermenters	$ 3,223,506
Harvest Tanks	$ 229,506
Stripping Column	$ 581,071
Double-effect Evaporator	$ 1,568,902
Rectifying Column	$ 367,000
Ethanol Product Storage Tanks	$ 339,373
Total Major Equipment Cost:	$ 6,309,358


Fuesl Recovery Heat Exchanger
0%
Fusel Oil Decanter
0%
Packed Distillation Column
1%
Fusel Oil Storage Tanks
2%
Ethanol Product Storage Tanks
5%
Rectifying Column
6%
Double-effect Evaporator
24%
Fermenters
49%
Stripping Column
9%
Harvest Tanks
4%

Packed Column Hydraulic Plot



Fusel Oil Uses

- Fusel Oil is used in:
    - Production of industrial solvents, flavoring agents, and plasticizers[1]
    - Burned to produce energy or added to diesel fuel[1]

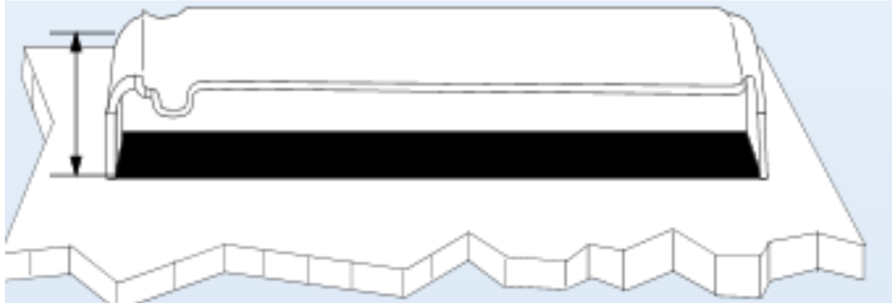
[1]dx.doi.org/10.1021/ie300665z, Ferreira et al., 2013

Why UNIQUAC-RK thermodynamics?

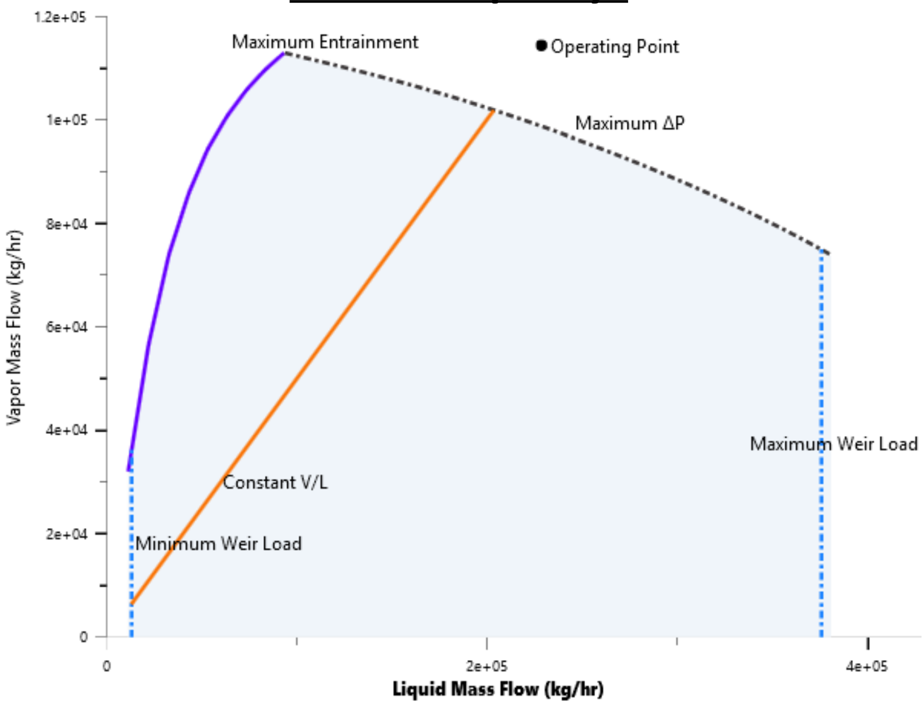
- UNIQUAC is best for strongly non-ideal liquid solutions and liquid-liquid equilibria.
  - The amounts of glucose dissolved in the water cause non-ideal tendencies.
- Redlich-Kwong equation of state method takes account non-ideal scenarios of vapor phase.
  - This occurs mostly in the first column, due to the large amounts of water and the small amount of fusel alcohol
    - Fusel alcohol’s boiling point > water’s boiling point
    - Theoretically, a lot more water would vaporize than fusel oil.

What is a Nutter-BDP Valve?

- Rectangular shaped valve set. Oriented Parallel to the liquid flow, allowing lateral vapor release.
  - Major project advantage-
    - Allows large amount of solid permeation between plates.



Bubble Cap Trays



Nutter-BDP Trays