Investigation of Batch Distillation Operating Modes

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Introduction

Distillation is a technique widely used by chemical engineers to separate and purify liquid compounds. It involves heating a mixture of liquids with different boiling points until they vaporize and rise through the distillation column, then condense along the height of the column as they cool.

This technique has a long history in alcohol production, pharmaceutical purification, and petroleum processing. The earliest use dates back to 3000 BCE in Mesopotamia and Egypt, where it was used to produce medicinal compounds and perfumes. Distillation has since advanced to meet precise specifications through fractional distillation.

Distillation knowledge is essential for chemical engineers to avoid instances like the 2005 British Petroleum's Texas City Refinery explosion. This incident arose from over pressuring the unit and resulted in 15 fatalities and 170 injured.

Objectives & Hypotheses

The purpose of this experiment is to explore pressure drop across the column, and column efficiency in different operating modes, as well as the impact of changing the reflux ratio on the column. The following predictions were made:

Experiment A: By increasing the boil-up rate, the vapor velocity will increase and therefore the pressure drop will increase in a square relationship according to the Darcy-Weisbach equation.

Experiment B: Column efficiency will increase with boil-up rate because more vapors will be produced to interact with the liquids in the column.

Experiment C: Column efficiency will increase with greater reflux ratio because the liquid will be recycled back into the column for further purification.

Materials & Methods

The parameters for each experiment and their respective trials are summarized below.

Exp. A

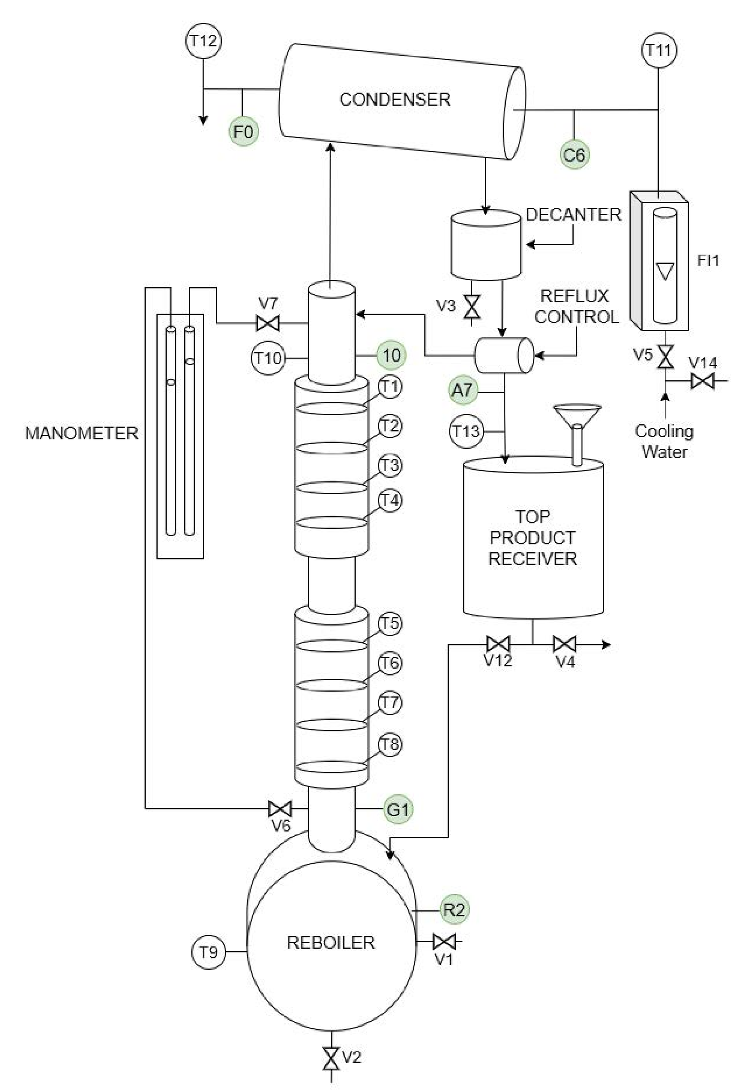
Trial	Power (kW)	Operating Mode
1	0.8	Total Reflux
2	0.7	
3	0.6	
4	0.4	
5	0.3	

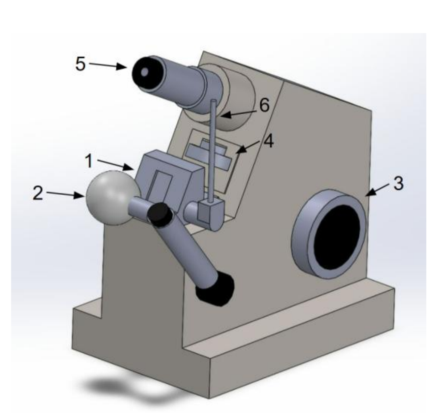
Exp. B

Trial	Power (kW)	Operating Mode
1	0.6	Total Reflux
2	0.5	
3	0.4	

Exp. C – Constant Reflux

Trial	Power (kW)	Reflux Ratio
1	0.6	5:1
2	0.6	3:1
3	0.6	7:1
4	0.5	5:1





Theory

Darcy-Weisbach Equation:

$$\Delta P = f_D \frac{L}{D} \frac{\rho v^2}{2}$$

$$v = \frac{V}{A}$$

ΔP: Pressure Drop
v: Fluid Velocity
V: Boil-Up Rate
A: Cross-Sectional Area

Fenske Equation:

$$N_{min} = \frac{\log\left[\left({x_d^A}/{x_d^B}\right)\left({x_b^A}/{x_b^B}\right)\right]}{\log[\alpha_{AB}]}$$

N_{min}: minimum # of trays
x_j^i : liquid mole fraction where *i* is the component and *j is* bottoms or distillate
α_{AB}: average relative volatility

Rectifying Operating Line:

$$y_n = \frac{R}{R+1} x_{n+1} + \frac{1}{R+1} x_d$$

y_n: vapor mol fraction
R: Reflux ratio (L/D)
x_{n+1}: liquid mole fraction
x_d: liquid mole fraction of distillate

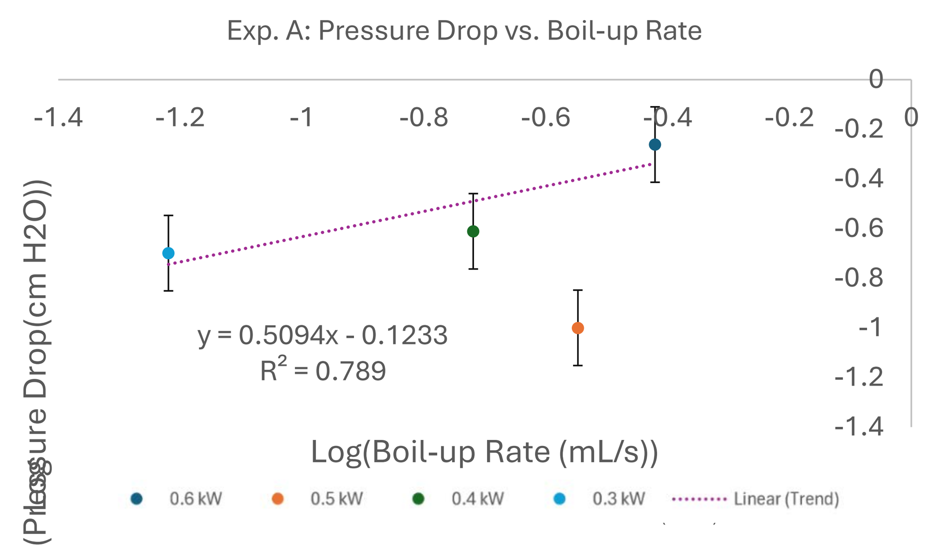
Column Efficiency:

$$E = \frac{n_{theoretical}}{n_{actual}} 100\%$$

E: efficiency of overall column
n: number of trays

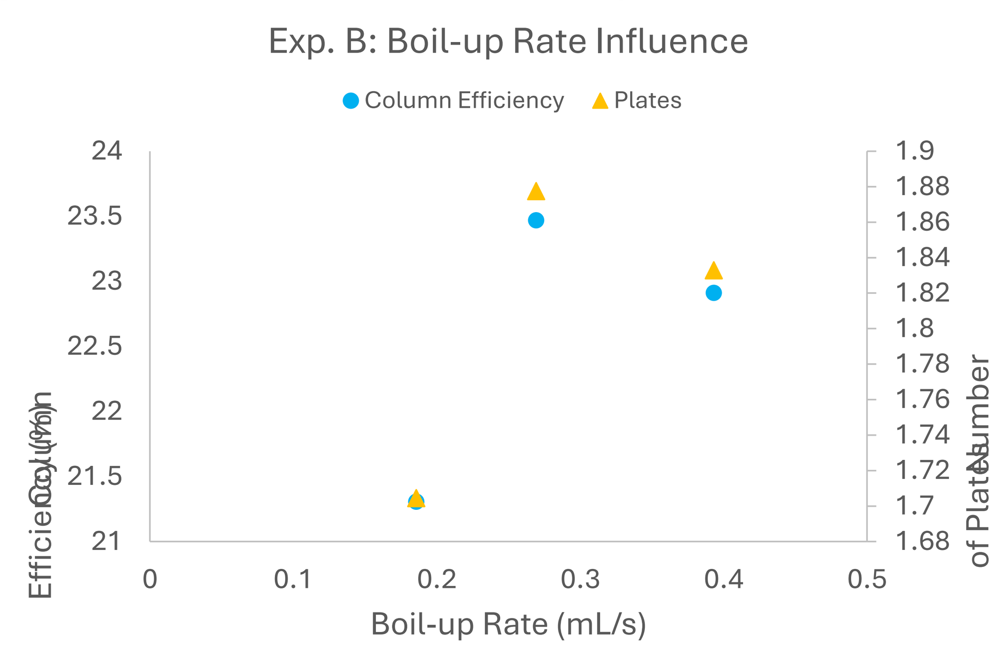
Results and Discussion

Experiment A: Pressure Drop with Respect To Boil-up Rate



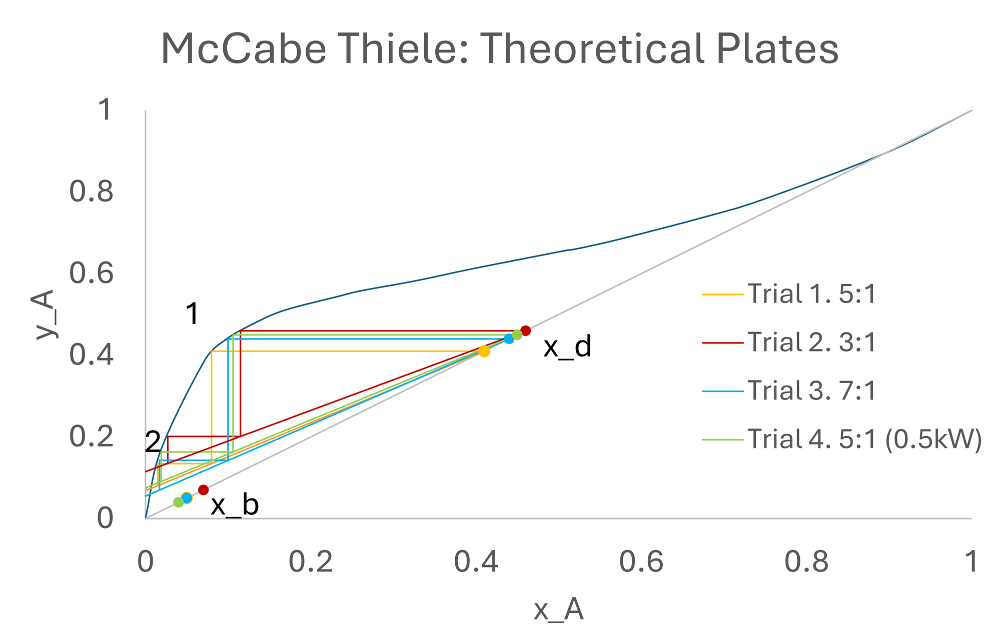
An outlier was seen at 0.5 kW power setting and removed to develop a linear trend on a log-log scale plot. Pressure drop and boil-up rate do not show the expected square relationship.

Experiment B: Column Efficiency Under Total Reflux



The lower two boil-up rates, at 0.4 kW and 0.5 kW, show an increase in efficiency as predicted. However, the third data point sees a reduction, negating the trend. A minimum of two trays is required.

Experiment C: Column Efficiency Under Constant Reflux



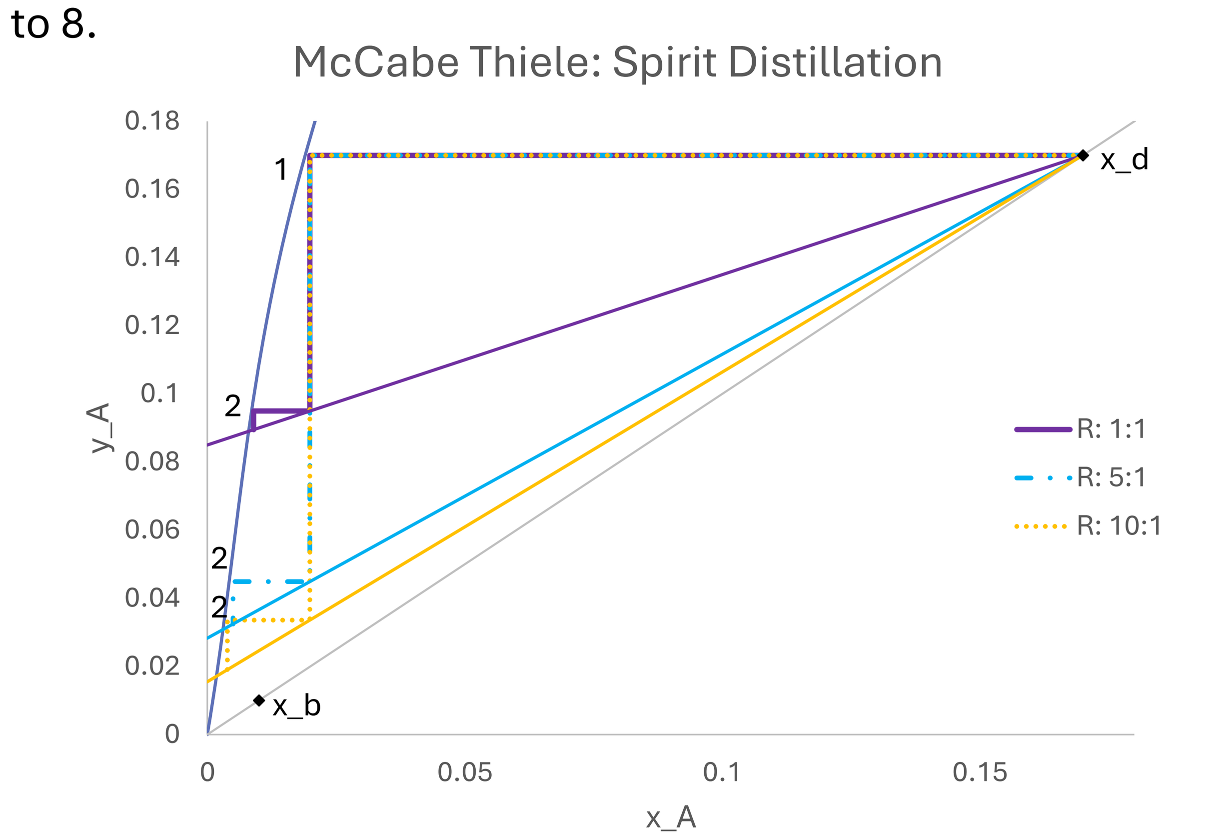
The rectifying line steepens as the reflux ratio increases. All trials resulted in needing two trays to obtain the respective bottoms mole fraction. This results in 25% column efficiency for all trials.

Design Extension

Suppose the UC Irvine Basketball team wanted to go to the Anthill Pub for a round on Peter, after soundly defeating their bitter rival, Long Beach State, in the homecoming game. Peter contacts a distillery to provide spirits with 40% alcohol by volume (ABV) to the team members of legal drinking age. The distillery needs to calculate the number of distillation plates and determine the best operating mode to distill a 40% ABV spirit to provide to the Anthill Pub.

Approach: Conduct Fenske analysis for total reflux operating mode and McCabe-Thiele analysis for constant reflux ratio operation.

Findings: Theoretically, two trays are needed to obtain 40% ABV distillate with a bottom's mole fraction of 0.01. Total reflux is not feasible in this scenario, as distillate must be removed to prepare for consumption. Using the previously determined 25% efficiency for constant reflux operation, the number of trays quadruples to 8.



Conclusion

Exp. A: Pressure drop is seen to increase with boil-up rate. However, the hypothesis that pressure drop increases in a square relation to boil-up rate is not supported.
Exp. B & C: The number of trays required to obtain a given bottoms composition did not change with the operating mode, boil-up rate, or reflux rate which opposed the hypotheses for experiment B and C.

Understanding batch distillation is necessary to provide a cost-effective separation method significant to pharmaceutical, fuel, and alcohol production.

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