

# Guidelines for the Number of Distillation Separation Stages



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## Continuous Distillation 1: McCabe-Thiele Method

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# Continuous Distillation 1: McCabe-Thiele Method

## 1. Review of Diagram Construction Method

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A mixture of 40 mol% benzene and 60 mol% toluene (boiling point liquid) is to be separated in a distillation column. The molar fractions of benzene in the distillate and bottoms are to be set to 0.90 and 0.10, respectively. Set the reflux ratio to 2.0, and find the number of required theoretical stages by the McCabe-Thiele method.

Rectifying section  
operating line

$$y_{n+1} = \frac{R}{R+1}x_n + \frac{1}{R+1}x_D$$

$y_{n+1}$  : Steam composition leaving stage  $n + 1$

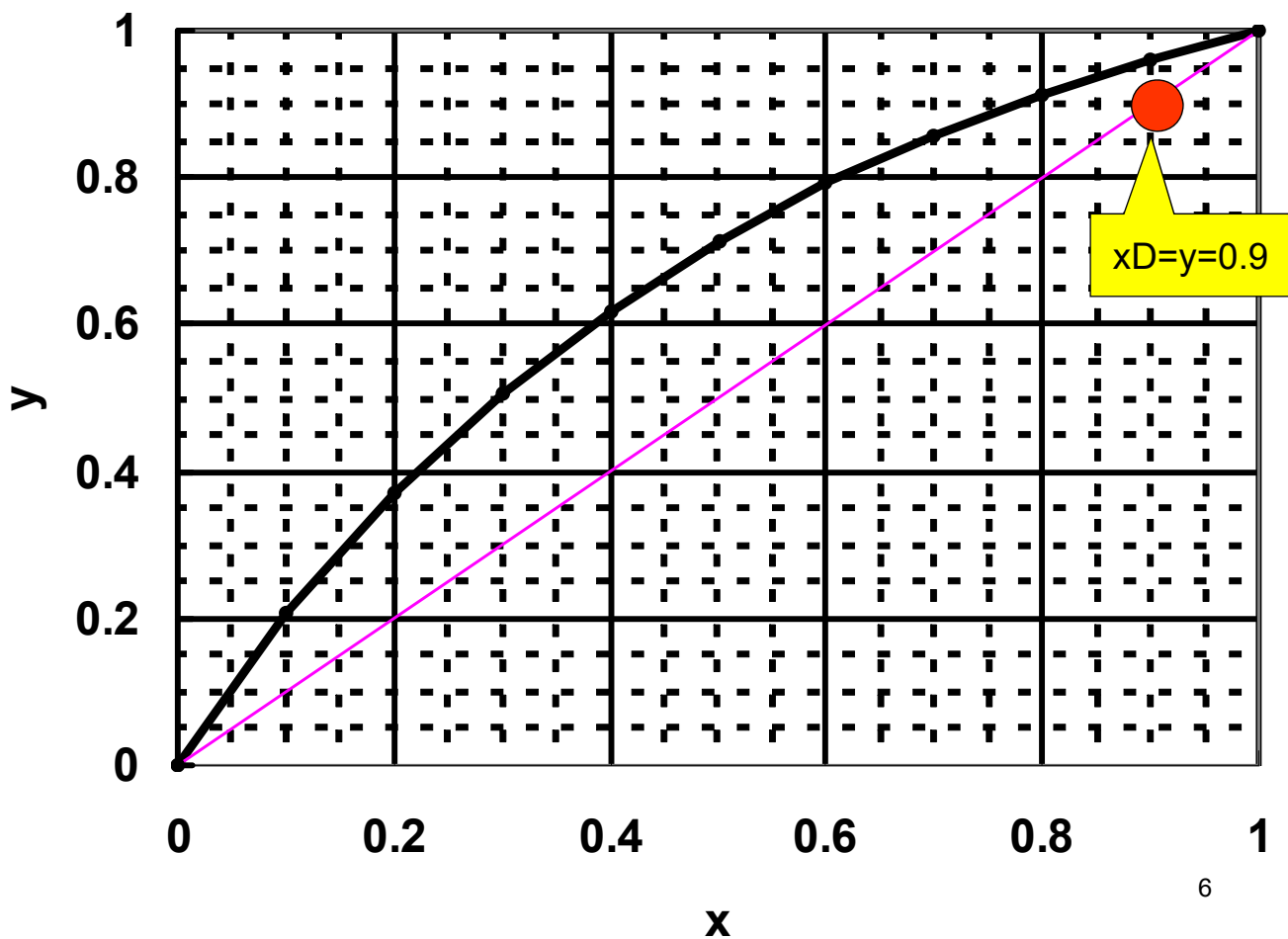
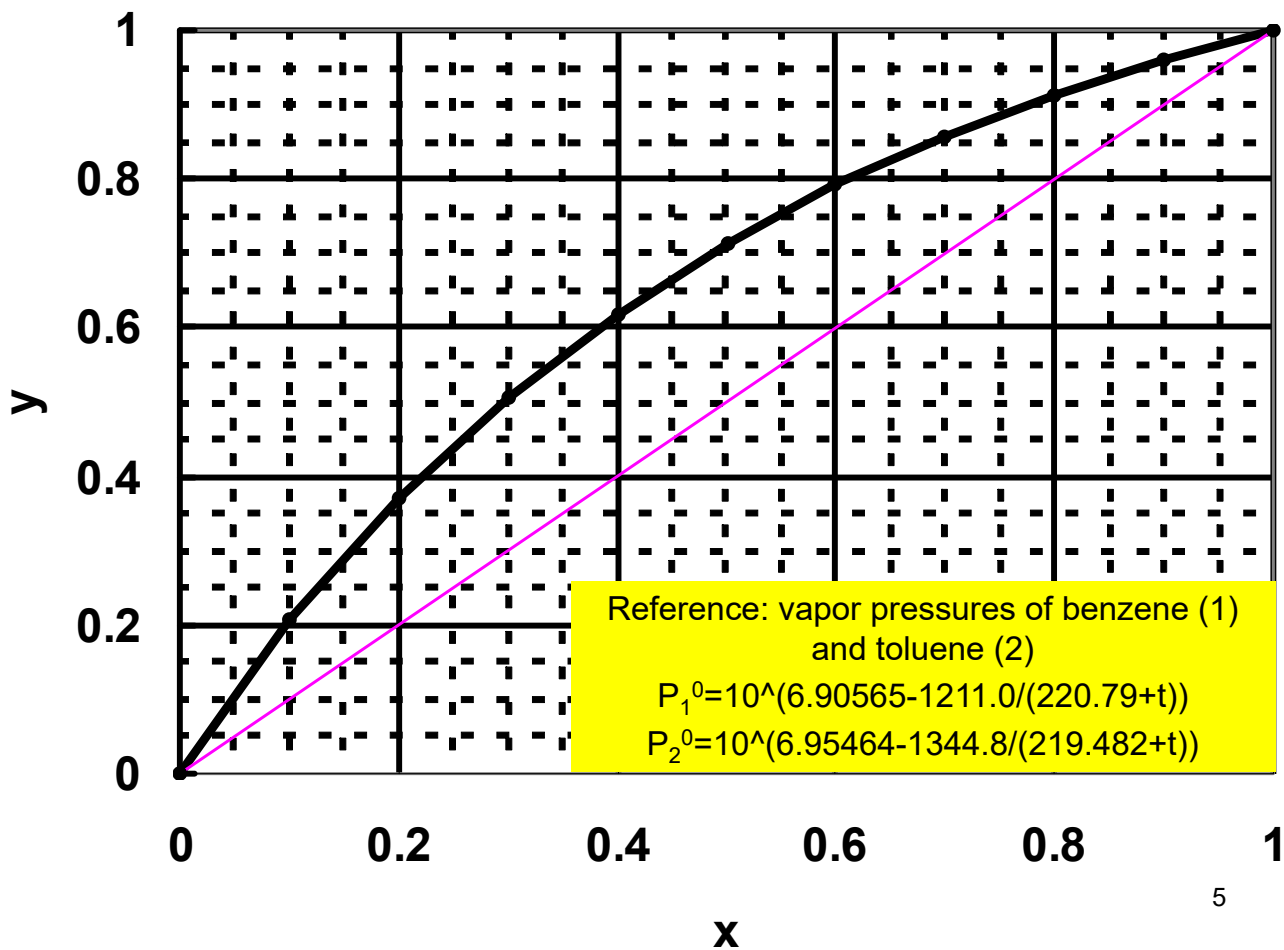
$x_n$  : Liquid composition leaving stage  $n$

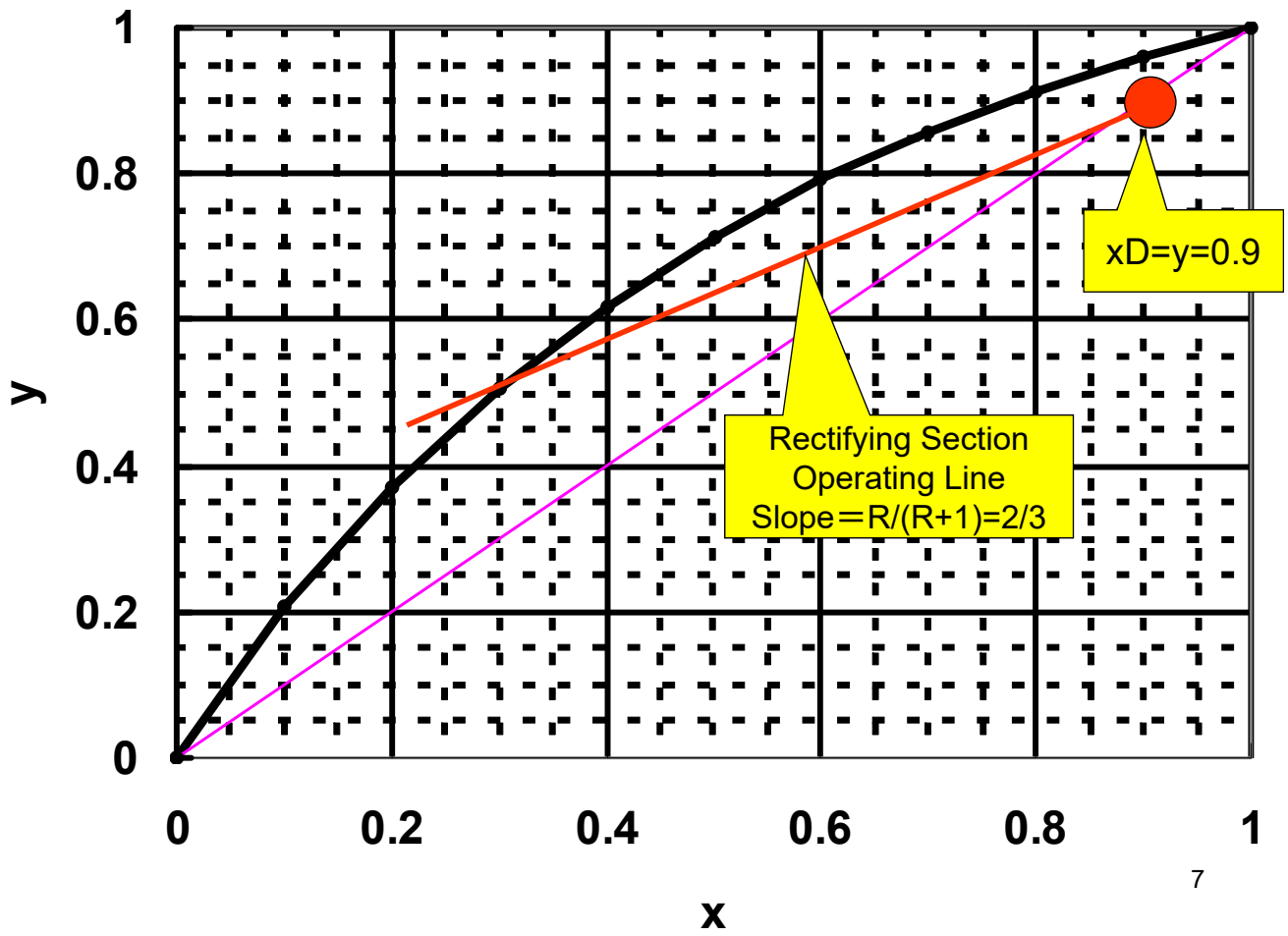
$x_D$  : Overhead product composition

$R$  : Reflux ratio

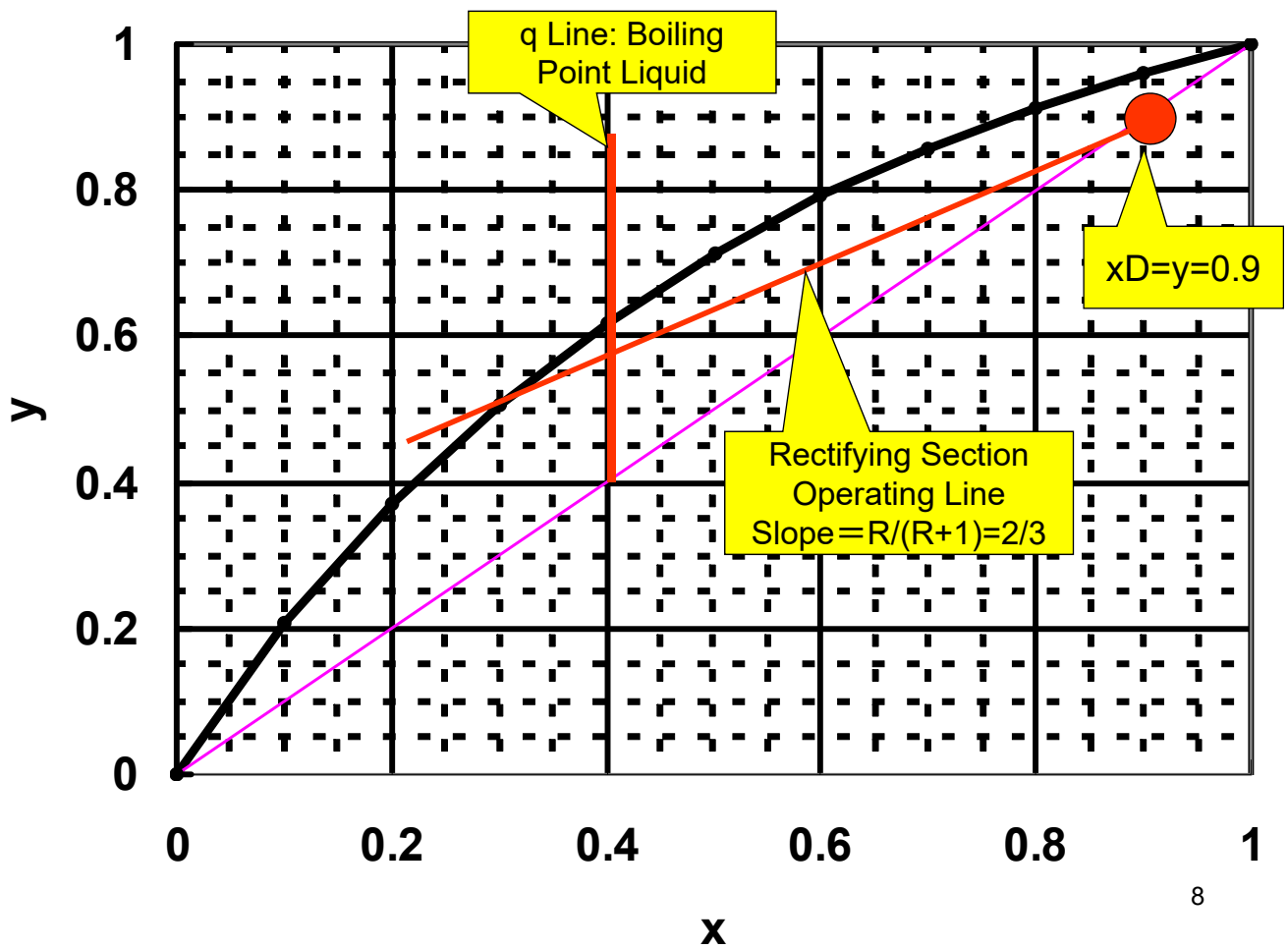
Operating line for diagram :  $y = \frac{R}{R+1}x + \frac{1}{R+1}x_D$

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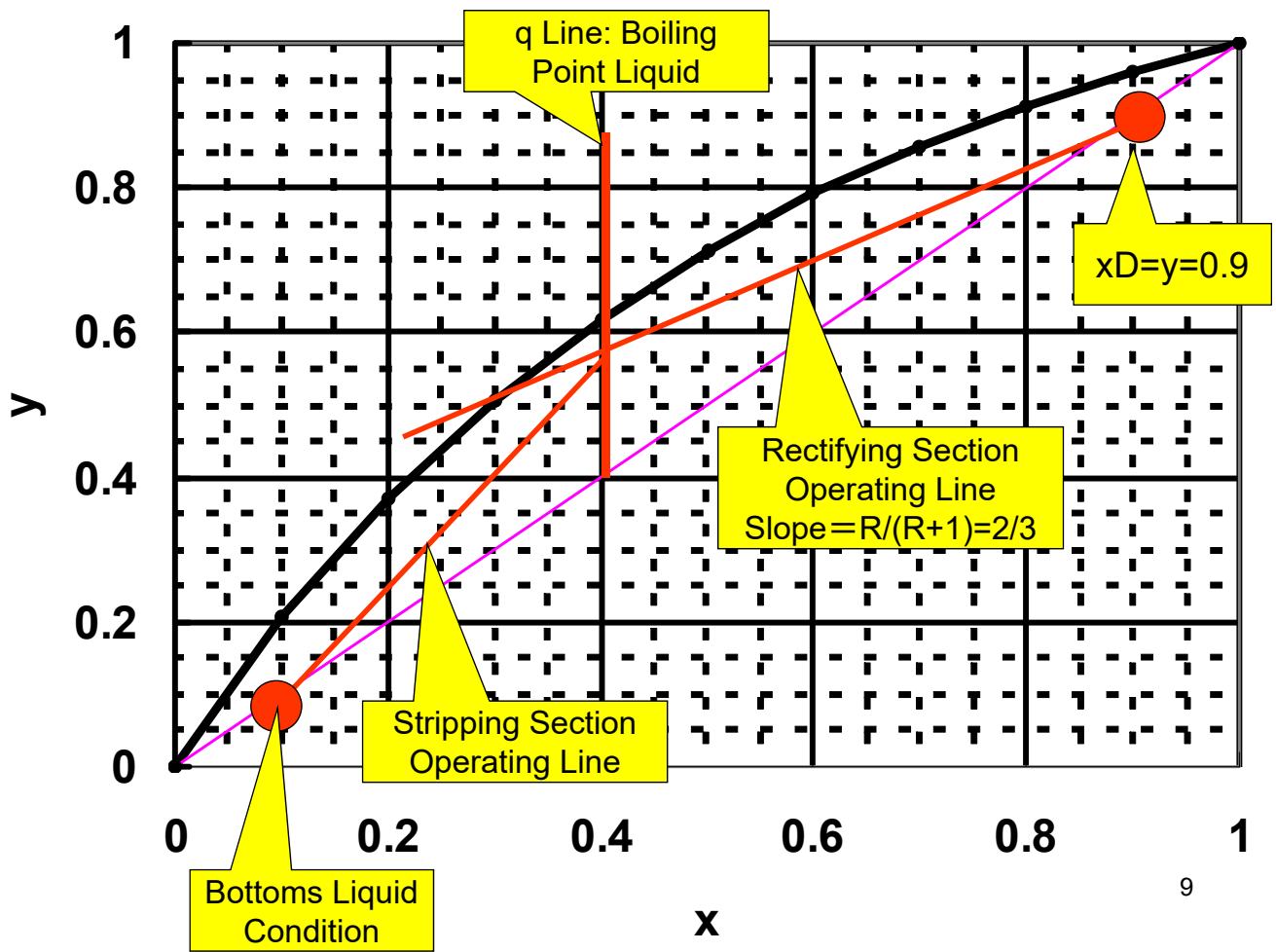




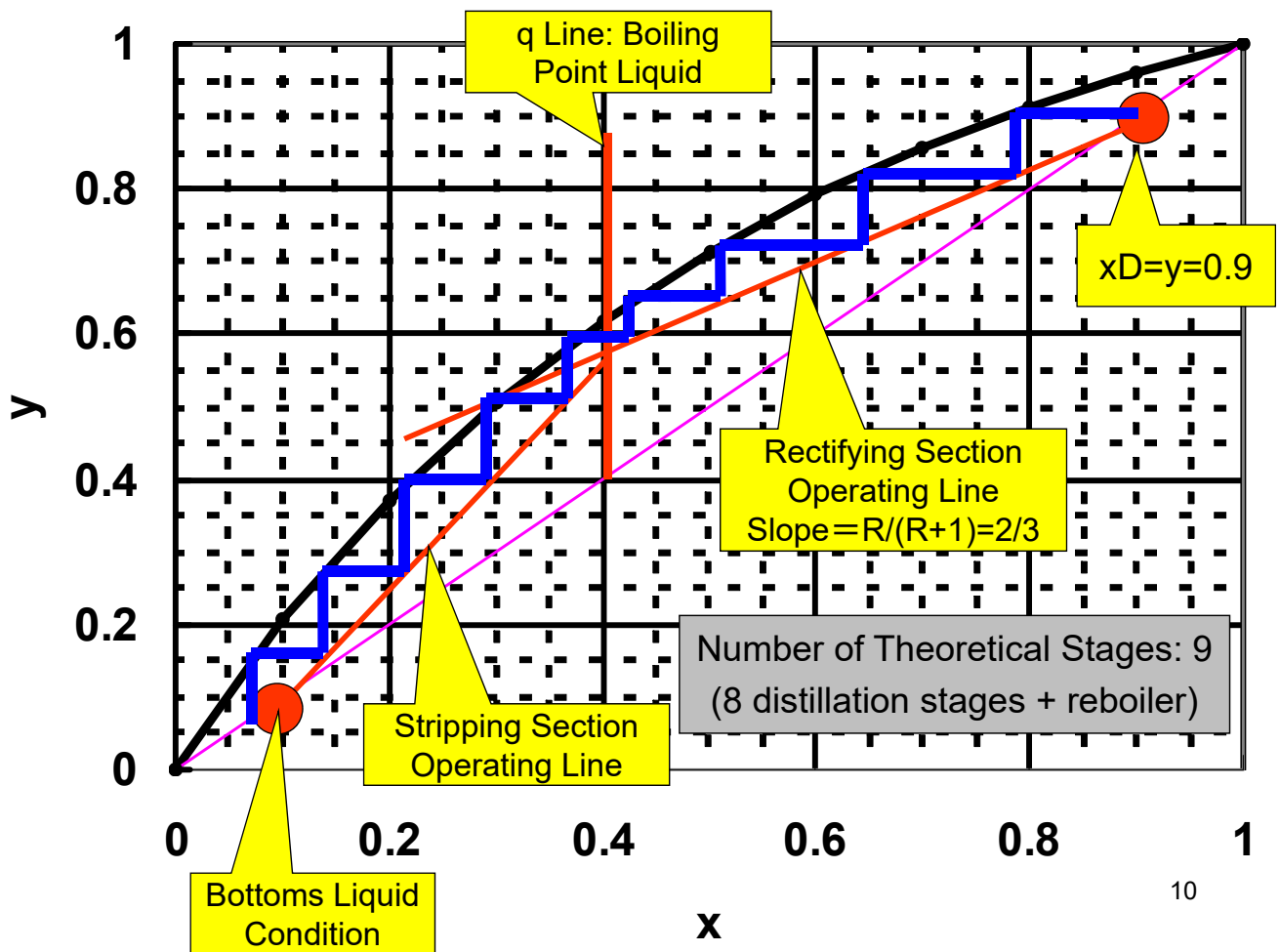
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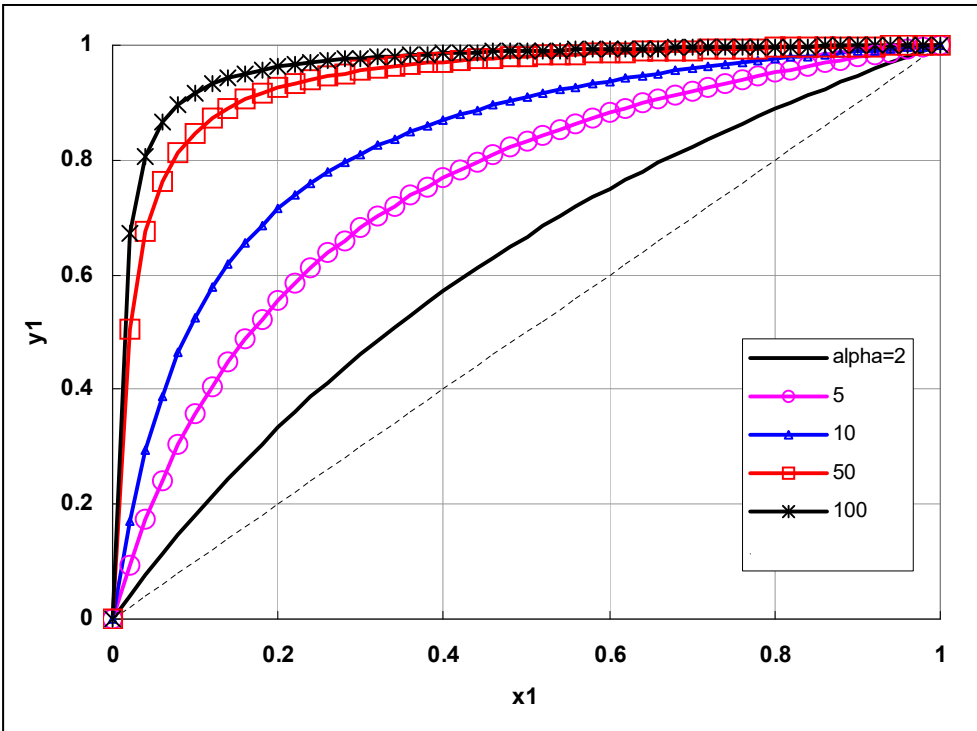


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# Continuous Distillation 1: McCabe-Thiele Method

## 2. Guidelines for Number of Stages

Although the number of stages is influenced by the reflux ratio and the purity at the top of the column, the difficulty of distillation separation can be pictured from the xy diagram.



The xy diagram can be calculated from the relative volatility

Relative volatility ( $\alpha_{12}$ ) = ratio of equilibrium ratios

$$\alpha \equiv K_1 / K_2 = \left( \frac{y_1}{x_1} \right) / \left( \frac{y_2}{x_2} \right) = \left( \frac{y}{x} \right) / \left( \frac{1-y}{1-x} \right) = \frac{y(1-x)}{x(1-y)}$$

Useful relationship  $y = \frac{\alpha x}{(\alpha - 1)x + 1}$

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The relative volatility is the ratio of the vapor pressures of the pure substances (ideal system)

In an ideal system Raoult's law holds  $Py_1 = x_1P_1^o$

$$Py_2 = x_2P_2^o$$

$$K_1 = \frac{y_1}{x_1} = \frac{P_1^o}{P}$$

$$K_2 = \frac{y_2}{x_2} = \frac{P_2^o}{P}$$

$$\alpha = K_1 / K_2 = P_1^o / P_2^o$$

In a system where Raoult's law holds, the relative volatility becomes the physically meaningful property value of the vapor pressure ratio.

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Continuous Distillation 1:  
McCabe-Thiele Method  
3. Examples of Guidelines

The boiling point difference  
between *p*-dichlorobenzene (PDB)  
and *o*-dichlorobenzene (ODB) is 6° C.  
Let us consider the difficulties of separation  
by distillation.

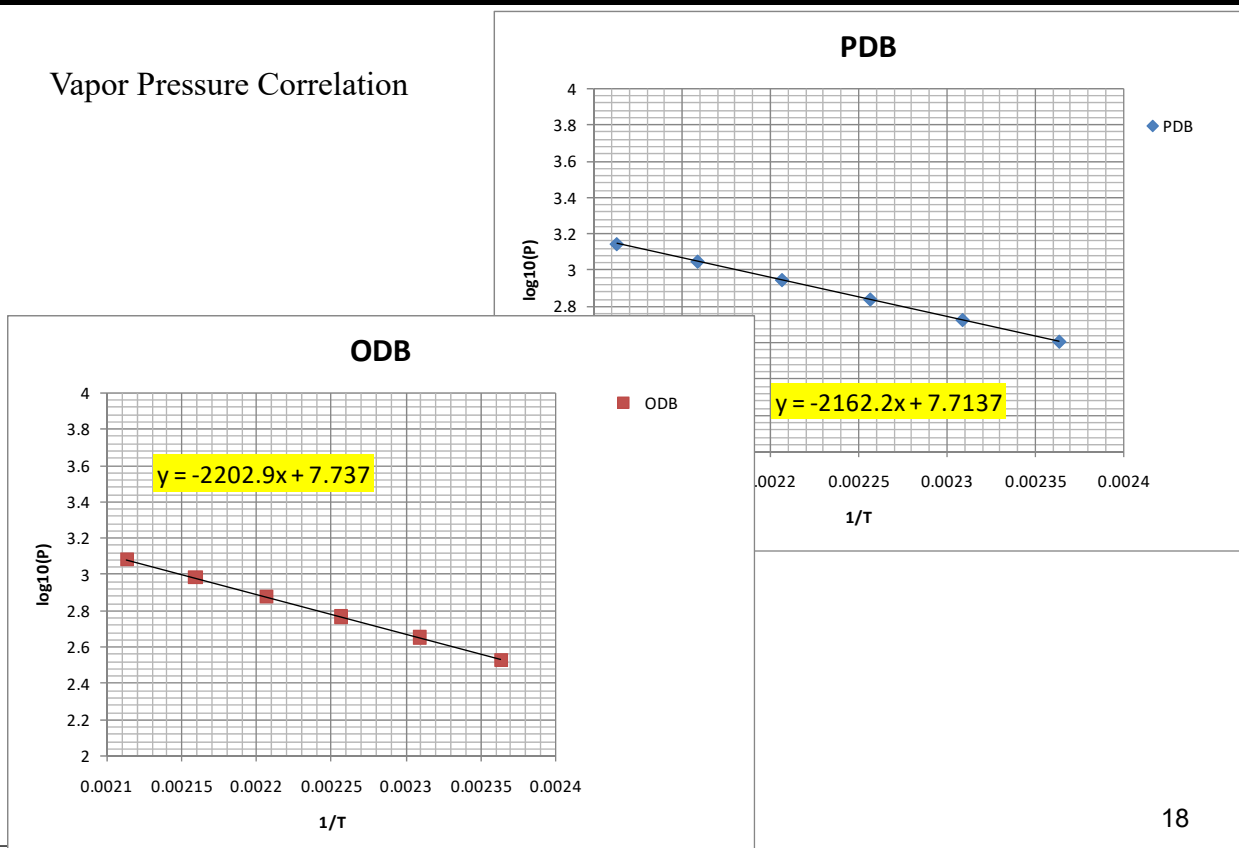


- Correlate the vapor pressure data of *p*-dichlorobenzene (PDB) and *o*-dichlorobenzene (ODB) with the Antoine equation.  
Use  $\text{Log}_{10}(P) = A - B/T$  as the Antoine equation.
- Calculate the relative volatility at 120° C, draw the xy diagram and consider the difficulty of separation by distillation.

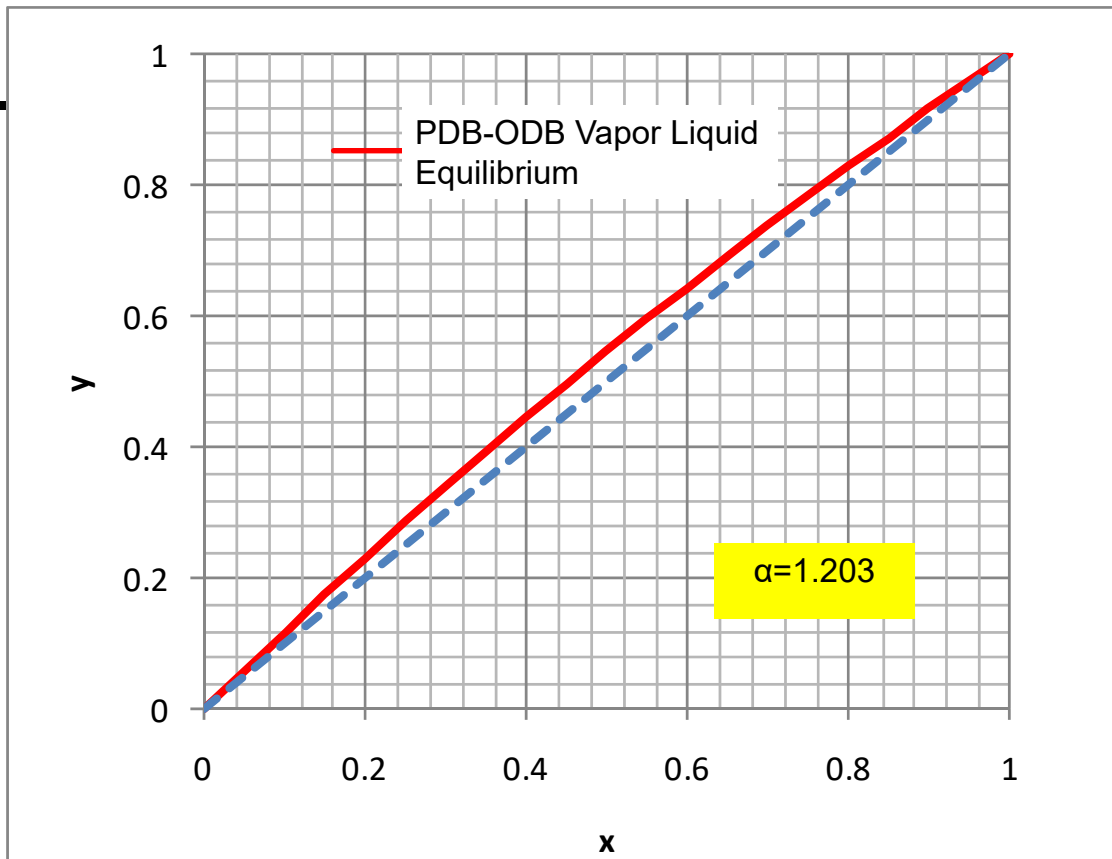
t, [°C]	150	160	170	180	190	200
PDB, [mmHg]	400.4165	527.7156	685.2758	877.8249	1110.406	1388.358
ODB, [mmHg]	338.3175	448.3665	585.2366	753.2029	956.8044	1200.809

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### Vapor Pressure Correlation



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Although it has not been determined exactly, it can be expected that the number of theoretical stages required for distillation will be very large.

## Continuous Distillation 2: Actual Plant Correlation

$$N_{\text{act}} = 1350 / \Delta T$$

$N_{\text{act}}$ : Actual number of distillation column stages

$\Delta T$ : Difference in the boiling points of the components to be separated

Satoru Kawai (Mitsubishi Kasei): "Process Sekkei ni-okeru Bunshi Kagaku Kougakuteki Shuhou  
(*in Japanese* : Molecular Chemical Engineering Methods in Process Design)",  
Recent Process Design Engineering Workshop organized by the Society of Chemical Engineers,  
Japan (November 27, 1987)

From this approximation method, it is possible to estimate the actual number of stages from the difference in the boiling points of the components very easily.

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## Batch Distillation: Rose Relationship

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**8・4・1 Roseの関係<sup>1)</sup>**  
 2成分系回分精留では還流比を一定に保てば、留出物中の低沸点成分の濃度は時間と共に減少する。しかし特別の場合を除けば、一般に留分の最初の40%が低沸点成分濃度95mol%以上の純度を有するように精留塔を設計しておけば十分であるが、このような場合の理論段数と還流比との関係を検討した結果、Roseはつぎの関係を得た。

$$\left. \begin{array}{l} 2.4/\log\alpha \leq R \leq 3.5/\log\alpha \\ 2.3/\log\alpha \leq S \leq 3.6/\log\alpha \end{array} \right\} \quad (8 \cdot 63)$$

$R$ は還流比、 $S$ はステップ数、 $\alpha$ は相対揮発度であり、もし塔内で変化するとき、平均値を採用すればよい。式(8・63)の範囲内に $R, S$ があれば、だいたいにおいて希望の分離が得られるのであるが、簡単には

$$S = R = 2.85/\log\alpha \quad (8 \cdot 64)$$

と考えてよい。ただし、これらの関係は原液の組成が10~90mol%である場合に限られる。

"Kagaku Kougaku Binran,  
 Revised 3rd ed. (in Japanese)"  
 p.552-553

In a binary system batch distillation, if the reflux ratio is kept constant, the concentration of the low boiling point component in the distillate decreases with time. However, except in special cases, it is generally sufficient to design the distillation column so that the first 40% of the distillate has a low-boiling point component concentration of 95 mol% purity or more. As a result of examining the relationship between the theoretical number of stages and the reflux ratio in such a case, Rose obtained the following relationships.

$$\left. \begin{array}{l} 2.4/\log\alpha \leq R \leq 3.5/\log\alpha \\ 2.3/\log\alpha \leq S \leq 3.6/\log\alpha \end{array} \right\} \quad (8.63)$$

Here,  $R$  is the reflux ratio,  $S$  is the number of steps, and  $\alpha$  is the relative volatility (if it varies within the column, an average value may be used). If  $R$  and  $S$  are within the range of Equation (8.63), the desired separation can be roughly obtained. These relationships can be simplified as,

$$S = R = 2.85/\log\alpha \quad (8.64)$$

Note that these relationships can be applied only when the composition of the feed solution is between 10 and 90 mol%.  
 "Rose, A. : Ind. Eng. Chem., 33, 594 (1941)"

Solutions for R&D to Design

## Rose's Relationship and Design Examples

System	Relative Volatility	$2.85/\log\alpha$	Number of theoretical stages	Operation reflux ratio	Remarks
1. Water / Polar Solvent	<b>6.1</b>	<b>3.6</b>	<b>5</b>	<b>2-3</b>	New column
2. Silane derivatives/ EDC	<b>2.4</b>	<b>7.5</b>	<b>7</b>	<b>1.5</b>	New column
3. Olefin	<b>1.2</b>	<b>36.0</b>	<b>20</b>	<b>40</b>	Column reassignment

- Cases 1 and 2: Since new columns are involved, these case-studies are focused mainly on Rose's relationship, and the number of stages is close to Rose's relationship. However, the reflux ratio is not that important.
- Case 3: There were only 20 theoretical stages in the column to be reassigned, and as a result of increasing the reflux ratio, it became close to that calculated by Rose's relationship.
- Setting both the number of stages and the reflux ratio to a value obtained from Rose's relationship appears to be an over specification.
- In the last example, the relative volatility is close to that of *o*-dichlorobenzene and *p*-dichlorobenzene. Batch distillation seems to have a comparatively better separation performance than continuous distillation.

- Whether for continuous or batch operation, it is important to use guidelines before performing distillation calculations in order to do an efficient investigation.
- It is difficult to develop guidance skills by using only a process simulator. It appears that these skills can be developed by comparing simulator results with methods that employ simple guidelines.