厚积薄发 开物成务

化工原理（II）

第九章 蒸馏

主讲人：曹睿

中国石油大学(北京)

操作线方程

【提问】

一、已分析测得连续精馏塔中某4股物料的浓度组成分别为0.62，0.70，0.75，0.82，试找出 y_7，y_6，x_7，x_6（塔板序列自上往下）的对应值：

y_6=<u>0.82</u>　y_7=<u>0.75</u>　x_6=<u>0.7</u>　x_7=<u>0.62</u>

（清华大学2001年）

二、精馏过程的操作线为直线，主要基于<u>B</u>。

A. 塔顶泡点回流　　B. 恒摩尔流假定

C. 理想物系　　D. 理论板假定

（浙江大学1999年）

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双组分连续精馏塔的计算

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05 设计型计算

5.1 理论板数的计算

5.2 回流比的选择

5.3 特殊情况理论板数的计算

五、设计型计算[124]

（一）理论板数的计算

1. 逐板计算法 —plate-to-plate calculation

2. 图解法—McCabe-Thiele method (1925)

3. 指数函数严格计算法—EFRC method（2012）

4. 简捷计算法—Gilliland method(1940)

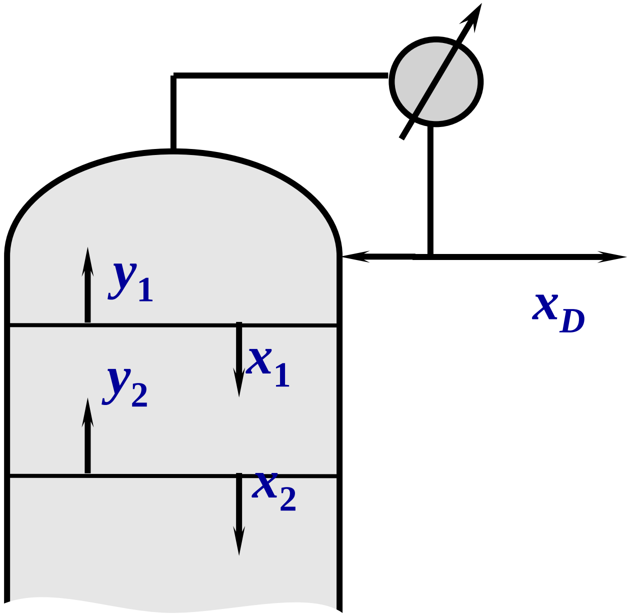
5. 指数函数简捷计算法—EFSC method（2014）

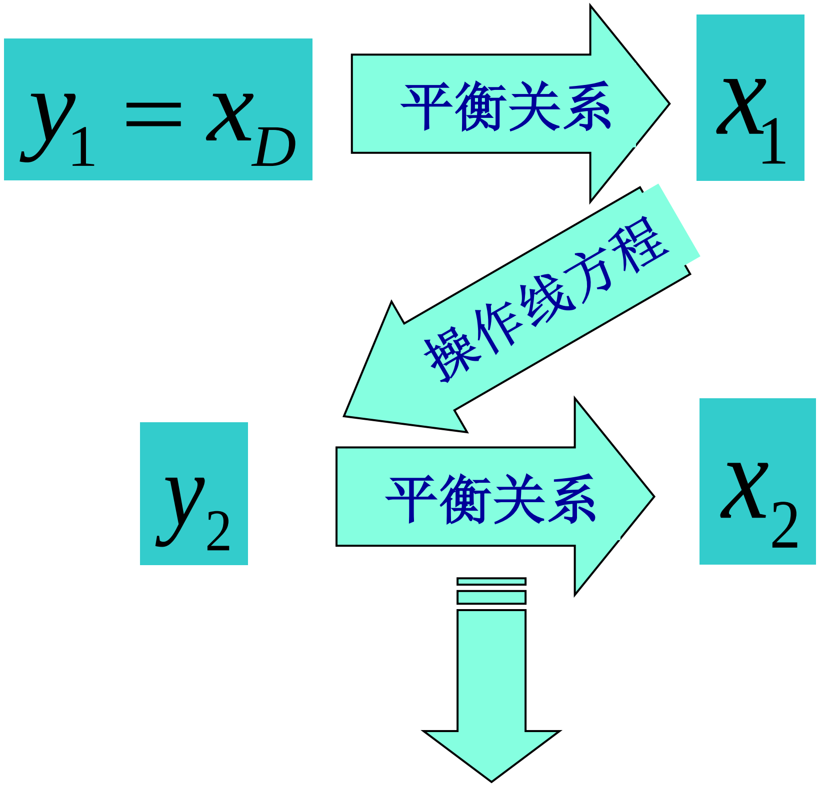
第五节 双组分连续精馏塔的计算

五、设计型计算[124]

（一）理论板数的计算

1. 逐板计算法



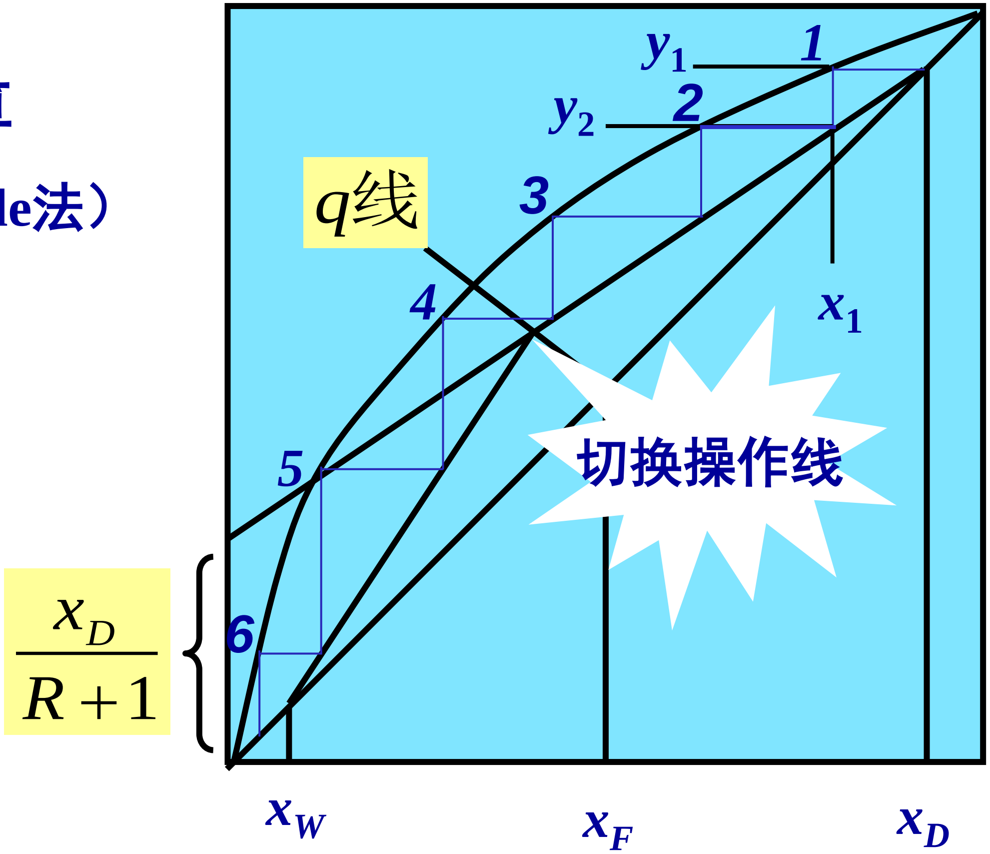

$y_1 = x_D$ —平衡关系→ x_1 —操作线方程→ y_2 —平衡关系→ x_2

第五节 双组分连续精馏塔的计算

五、设计型计算[124]

（一）理论板数的计算

2. 图解法（McCabe-Thiele法）



进料板：第四块

N_T=5.6块

分凝器、再沸器

相当于一块理论板

第五节 双组分连续精馏塔的计算

1. 逐板计算法

- $y_1 = x_D$，交替使用精馏段操作线与相平衡线方程；
- $x_{m+1} < x_q$切换为提馏段操作线，精馏段操作线与q线交点为（x_q , y_q）；常用$x_{m+1} < x_F$试算代替。
- $x_n < x_W$，$n = N_T$ 。
- 进料板位置$m+1$取整数，N_T可以为小数，内插计算。
- 精馏段操作线：（x_D, x_D）点和（x_q , y_q）点，

  提馏段操作线：（x_q , y_q）点和（x_W, x_W）点，

  q线：（x_q , y_q）点和（x_W , x_W）点。

第五节 双组分连续精馏塔的计算

五、设计型计算[124]

（一）理论板数的计算

3. 适宜进料位置

跨交点切换操作线

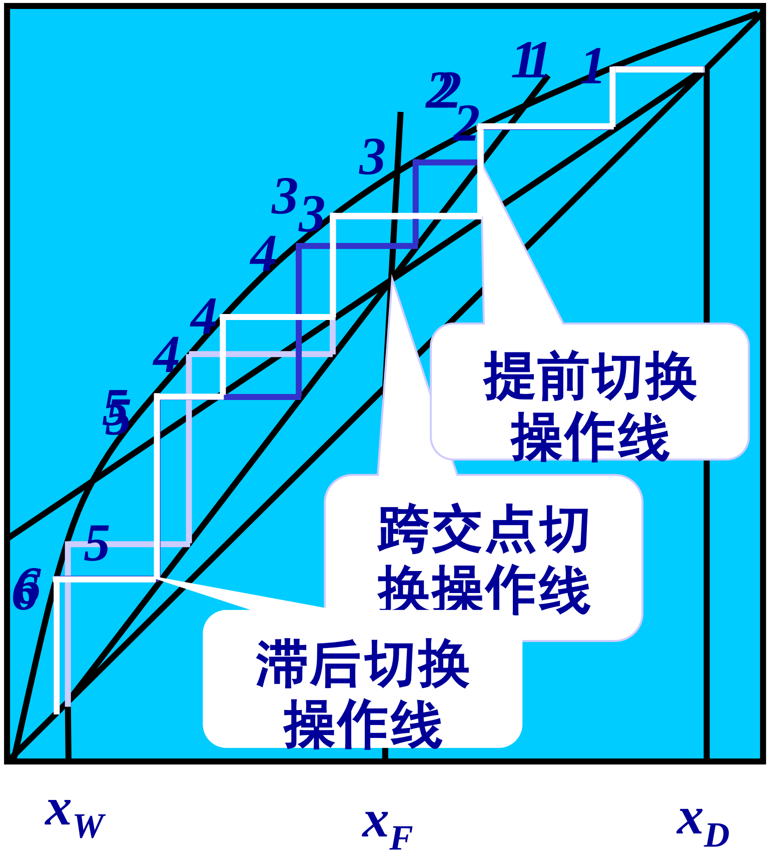
——适宜进料位置

提前切换操作线

——理论板数增加

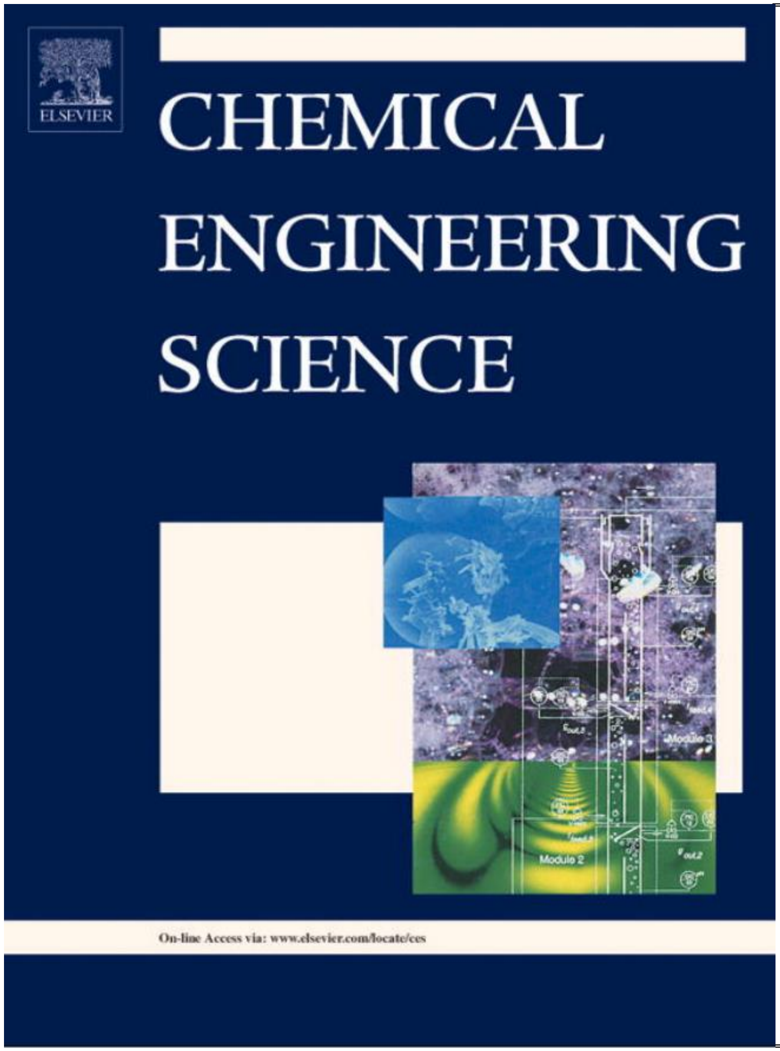
滞后切换操作线

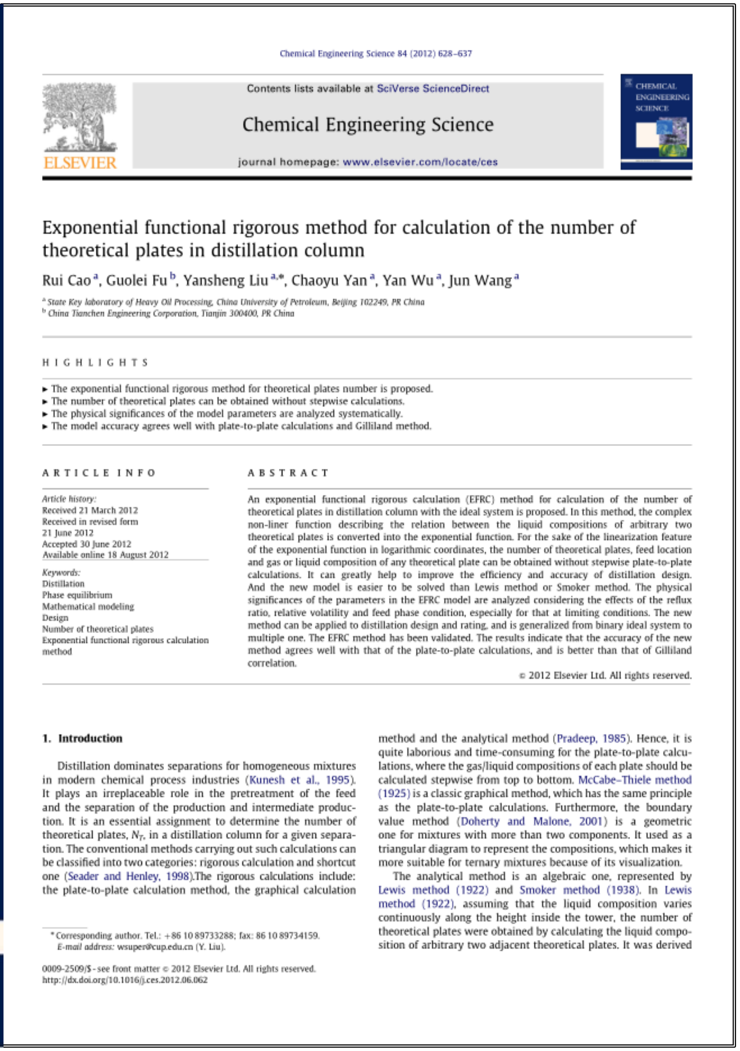
——理论板数增加



第五节 双组分连续精馏塔的计算

3. 指数函数严格计算法（EFRC法）





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Exponential functional rigorous method for calculation of the number of theoretical plates in distillation column

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HIGHLIGHTS

- The exponential functional rigorous method for theoretical plates number is proposed.
- The number of theoretical plates can be obtained without stepwise calculations.
- The physical significances of the model parameters are analyzed systematically.
- The model accuracy agrees well with plate-to-plate calculations and Gilliland method.

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ABSTRACT

An exponential functional rigorous calculation (EFRC) method for calculation of the number of theoretical plates in distillation column with the ideal system is proposed. In this method, the complex non-liner function describing the relation between the liquid compositions of arbitrary two theoretical plates is converted into the exponential function. For the sake of the linearization feature of the exponential function in logarithmic coordinates, the number of theoretical plates, feed location and gas or liquid composition of any theoretical plate can be obtained without stepwise plate-to-plate calculations. It can greatly help to improve the efficiency and accuracy of distillation design. And the new model is easier to be solved than Lewis method or Smoker method. The physical significances of the parameters in the EFRC model are analyzed considering the effects of the reflux ratio, relative volatility and feed phase condition, especially for that at limiting conditions. The new method can be applied to distillation design and rating, and is generalized from binary ideal system to multiple one. The EFRC method has been validated. The results indicate that the accuracy of the new method agrees well with that of the plate-to-plate calculations, and is better than that of Gilliland correlation.

1. Introduction

Distillation dominates separations for homogeneous mixtures in modern chemical process industries (Kunesh et al., 1995). It plays an irreplaceable role in the pretreatment of the feed and the separation of the production and intermediate production. It is an essential assignment to determine the number of theoretical plates, N_T, in a distillation column for a given separation. The conventional methods carrying out such calculations can be classified into two categories: rigorous calculation and shortcut one (Seader and Henley, 1998).The rigorous calculations include: the plate-to-plate calculation method, the graphical calculation method and the analytical method (Pradeep, 1985). Hence, it is quite laborious and time-consuming for the plate-to-plate calculations, where the gas/liquid compositions of each plate should be calculated stepwise from top to bottom. McCabe–Thiele method (1925) is a classic graphical method, which has the same principle as the plate-to-plate calculations. Furthermore, the boundary value method (Doherty and Malone, 2001) is a geometric one for mixtures with more than two components. It used as a triangular diagram to represent the compositions, which makes it more suitable for ternary mixtures because of its visualization.

The analytical method is an algebraic one, represented by Lewis method (1922) and Smoker method (1938). In Lewis method (1922), assuming that the liquid composition varies continuously along the height inside the tower, the number of theoretical plates were obtained by calculating the liquid composition of arbitrary two adjacent theoretical plates. It was derived

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第五节 双组分连续精馏塔的计算

指数函数简捷计算法（EFSC法）

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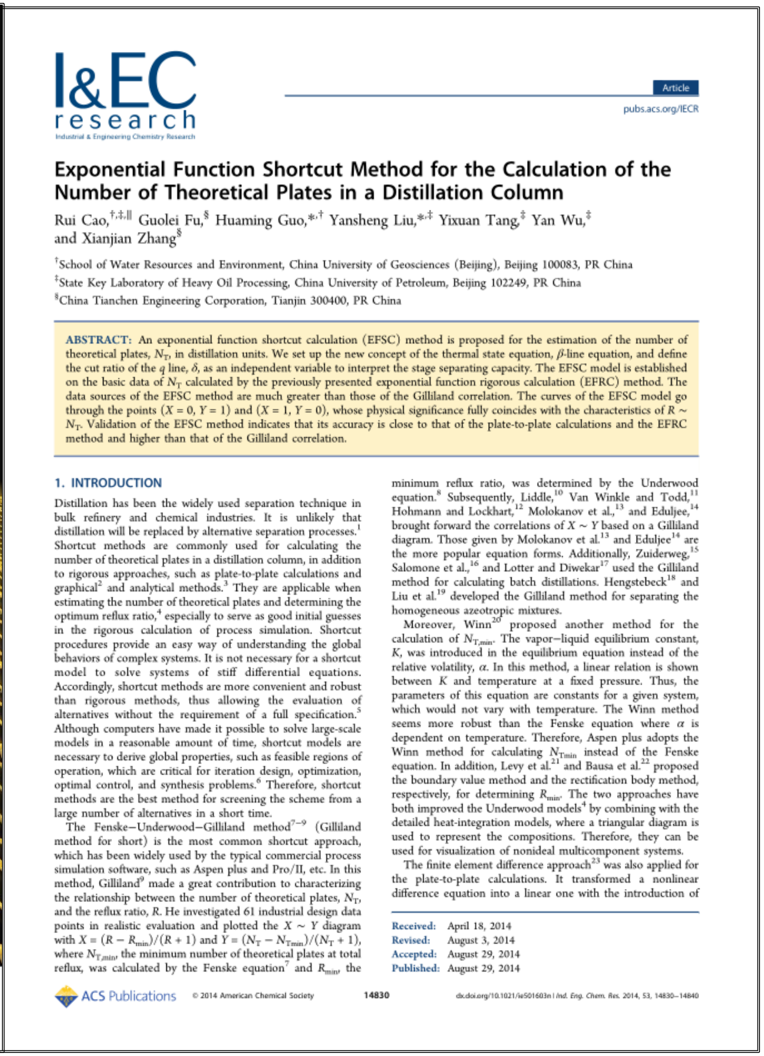

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Exponential Function Shortcut Method for the Calculation of the Number of Theoretical Plates in a Distillation Column

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ABSTRACT: An exponential function shortcut calculation (EFSC) method is proposed for the estimation of the number of theoretical plates, N_T, in distillation units. We set up the new concept of the thermal state equation, β-line equation, and define the cut ratio of the q line, δ, as an independent variable to interpret the stage separating capacity. The EFSC model is established on the basic data of N_T calculated by the previously presented exponential function rigorous calculation (EFRC) method. The data sources of the EFSC method are much greater than those of the Gilliland correlation. The curves of the EFSC model go through the points ($X = 0, Y = 1$) and ($X = 1, Y = 0$), whose physical significance fully coincides with the characteristics of $R \sim N_T$. Validation of the EFSC method indicates that its accuracy is close to that of the plate-to-plate calculations and the EFRC method and higher than that of the Gilliland correlation.

1. INTRODUCTION

Distillation has been the widely used separation technique in bulk refinery and chemical industries. It is unlikely that distillation will be replaced by alternative separation processes.[1] Shortcut methods are commonly used for calculating the number of theoretical plates in a distillation column, in addition to rigorous approaches, such as plate-to-plate calculations and graphical[2] and analytical methods.[3] They are applicable when estimating the number of theoretical plates and determining the optimum reflux ratio,[4] especially to serve as good initial guesses in the rigorous calculation of process simulation. Shortcut procedures provide an easy way of understanding the global behaviors of complex systems. It is not necessary for a shortcut model to solve systems of stiff differential equations. Accordingly, shortcut methods are more convenient and robust than rigorous methods, thus allowing the evaluation of alternatives without the requirement of a full specification.[5] Although computers have made it possible to solve large-scale models in a reasonable amount of time, shortcut models are necessary to derive global properties, such as feasible regions of operation, which are critical for iteration design, optimization, optimal control, and synthesis problems.[6] Therefore, shortcut methods are the best method for screening the scheme from a large number of alternatives in a short time.

The Fenske–Underwood–Gilliland method[7−9] (Gilliland method for short) is the most common shortcut approach, which has been widely used by the typical commercial process simulation software, such as Aspen plus and Pro/II, etc. In this method, Gilliland[9] made a great contribution to characterizing the relationship between the number of theoretical plates, N_T, and the reflux ratio, R. He investigated 61 industrial design data points in realistic evaluation and plotted the $X \sim Y$ diagram with $X = (R - R_{min})/(R + 1)$ and $Y = (N_T - N_{Tmin})/(N_T + 1)$, where $N_{T,min}$, the minimum number of theoretical plates at total reflux, was calculated by the Fenske equation[7] and R_{min}, the minimum reflux ratio, was determined by the Underwood equation.[8] Subsequently, Liddle,[10] Van Winkle and Todd,[11] Hohmann and Lockhart,[12] Molokanov et al.,[13] and Eduljee,[14] brought forward the correlations of $X \sim Y$ based on a Gilliland diagram. Those given by Molokanov et al.[13] and Eduljee[14] are the more popular equation forms. Additionally, Zuiderweg,[15] Salomone et al.,[16] and Lotter and Diwekar[17] used the Gilliland method for calculating batch distillations. Hengstebeck[18] and Liu et al.[19] developed the Gilliland method for separating the homogeneous azeotropic mixtures.

Moreover, Winn[20] proposed another method for the calculation of $N_{T,min}$. The vapor–liquid equilibrium constant, K, was introduced in the equilibrium equation instead of the relative volatility, α. In this method, a linear relation is shown between K and temperature at a fixed pressure. Thus, the parameters of this equation are constants for a given system, which would not vary with temperature. The Winn method seems more robust than the Fenske equation where α is dependent on temperature. Therefore, Aspen plus adopts the Winn method for calculating N_{Tmin} instead of the Fenske equation. In addition, Levy et al.[21] and Bausa et al.[22] proposed the boundary value method and the rectification body method, respectively, for determining R_{min}. The two approaches have both improved the Underwood models[4] by combining with the detailed heat-integration models, where a triangular diagram is used to represent the compositions. Therefore, they can be used for visualization of nonideal multicomponent systems.

The finite element difference approach[23] was also applied for the plate-to-plate calculations. It transformed a nonlinear difference equation into a linear one with the introduction of

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第五节 双组分连续精馏塔的计算

3. 指数函数严格计算法（EFRC法）

exponential function

$$\begin{tikzcd}
Z_n \arrow[r] \arrow[d, leftrightarrow] & Z_{n-1} \arrow[r, phantom, "\cdots"] \arrow[d, leftrightarrow] & Z_i \arrow[r, phantom, "\cdots"] \arrow[d, leftrightarrow, "Z_i=f(X_i)"'] & Z_2 \arrow[r] \arrow[d, leftrightarrow] & Z_1 \arrow[r, Rightarrow] \arrow[d, leftrightarrow] & Z_{i+1}=kZ_i \\
X_n \arrow[r] & X_{n-1} \arrow[r, phantom, "\cdots"] & X_i \arrow[r, phantom, "\cdots"] & X_2 \arrow[r] & X_1 \arrow[r, Rightarrow] & X_{i+1}=\dfrac{AX_i+B}{CX_i+D}
\end{tikzcd}$$

non-linear function

$$Z_{n+1}=k^n$$

$$Z_i=\frac{x_i+U}{x_i+V}$$

$$N_R=\frac{\lg(Z_n/Z_1)}{\lg K}+1=\frac{\lg\left(\dfrac{x_q+U}{x_q+V}\Big/\dfrac{x_1+U}{x_1+V}\right)}{\lg K}+1$$

$$N_S=\frac{\lg(Z_n/Z_1)}{\lg K}=\frac{\lg\left(\dfrac{x_W+U}{x_W+V}\Big/\dfrac{x_q+U}{x_q+V}\right)}{\lg K}$$

逐板法可用

EFRC法代替。

第五节 双组分连续精馏塔的计算

$$N_R = \frac{\lg(Z_n / Z_1)}{\lg K} + 1 = \frac{\lg\left(\dfrac{x_q + U}{x_q + V} \Big/ \dfrac{x_1 + U}{x_1 + V}\right)}{\lg K} + 1$$

$$N_S = \frac{\lg(Z_n / Z_1)}{\lg K} = \frac{\lg\left(\dfrac{x_W + U}{x_W + V} \Big/ \dfrac{x_q + U}{x_q + V}\right)}{\lg K}$$

可以解析求出N_T、进料位置或任意板的y、x，只要理想体系和恒摩尔流假定成立，逐板法可用EFRC法代替。

第五节 双组分连续精馏塔的计算

【例题】——理论板数及进料位置

已知苯—甲苯物系：

$x_F = 0.25$, $x_D = 0.98$, $x_W = 0.085$, $a = 2.47$, $R = 5$, $q = 1$,

塔顶为全凝器，泡点回流。

求：理论板数及进料位置。

第五节 双组分连续精馏塔的计算

【例题】——理论板数及进料位置

- R 2.63 2.8 3 4 **5** 50 1000 10000
- N_T 29 18 16 12 **10** 8 7 7

- 全回流， N_T最少
- 最小回流比，N_T趋于无穷大

第九章　蒸馏

CONTENT

05 设计型计算

第五节 双组分连续精馏塔的计算

五、设计型计算[137]

（二）回流比的选择

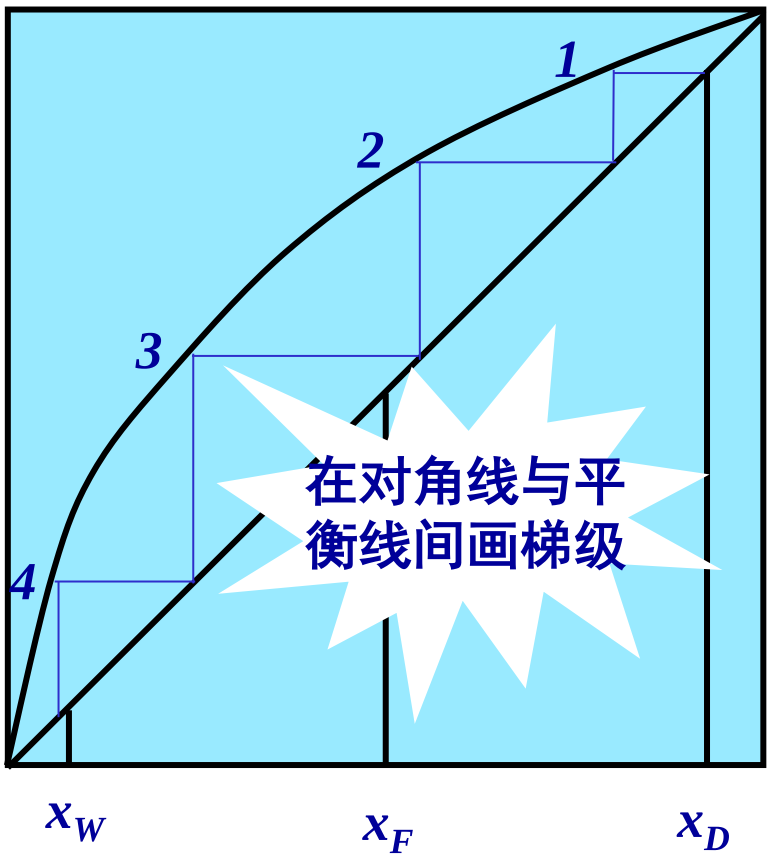
1. 全回流和最少理论板数

$F = 0$、$D = 0$、$W = 0$；

- 操作线方程为：$y_{n+1} = x_n$；
- $R \to \infty$、$N \to N_{\min}$。

第五节 双组分连续精馏塔的计算

五、设计型计算[137]



在对角线与平衡线间画梯级

最少理论板数为四块

Fenske方程

$$N_{\min} = \frac{\lg\left[\left(\frac{x_A}{x_B}\right)_D \left(\frac{x_B}{x_A}\right)_W\right]}{\lg \alpha_m}$$

塔顶全凝器，塔底再沸器

$$N_{\min,Final} = N_{\min} + 1$$

塔顶分凝器，塔底再沸器

$$N_{\min,Final} = N_{\min} + 2$$

第五节 双组分连续精馏塔的计算

$y_{n+1} = x_n$ 且 $\left(\frac{y_A}{y_B}\right)_n = \alpha\left(\frac{x_A}{x_B}\right)_n$

$(y_A)_1 = (x_A)_D \qquad (y_B)_1 = (x_B)_D$

$$\left(\frac{x_A}{x_B}\right)_D = \left(\frac{y_A}{y_B}\right)_1 = \alpha_1\left(\frac{x_A}{x_B}\right)_1$$

$$\left(\frac{x_A}{x_B}\right)_D = \alpha_1\left(\frac{x_A}{x_B}\right)_1 = \alpha_1\left(\frac{y_A}{y_B}\right)_2 = \alpha_1\alpha_2\left(\frac{x_A}{x_B}\right)_2$$

依此逐板推算，共经过$(N-1)$层塔板，一直到塔釜为止，得：

$$\left(\frac{x_A}{x_B}\right)_D = \alpha_1\alpha_2\cdots\alpha_{N-1}\alpha_W\left(\frac{x_A}{x_B}\right)_W = \bar{\alpha}^{N_{\min}}\left(\frac{x_A}{x_B}\right)_W \qquad \bar{\alpha} = \sqrt{\alpha_1\alpha_W}$$

Fenske 方程： $N_{\min} = \dfrac{\lg\left[\left(\frac{x_A}{x_B}\right)_D\left(\frac{x_B}{x_A}\right)_W\right]}{\lg\bar{\alpha}}$ （包括再沸器）

第五节 双组分连续精馏塔的计算

五、设计型计算[139]

（二）回流比的选择

2. 最小回流比

$N \to \infty$，塔内出现恒浓区；

- 操作线与平衡线必有交点 。

$$R_{\min} = \frac{x_D - y_e}{y_e - x_e}$$

第五节 双组分连续精馏塔的计算

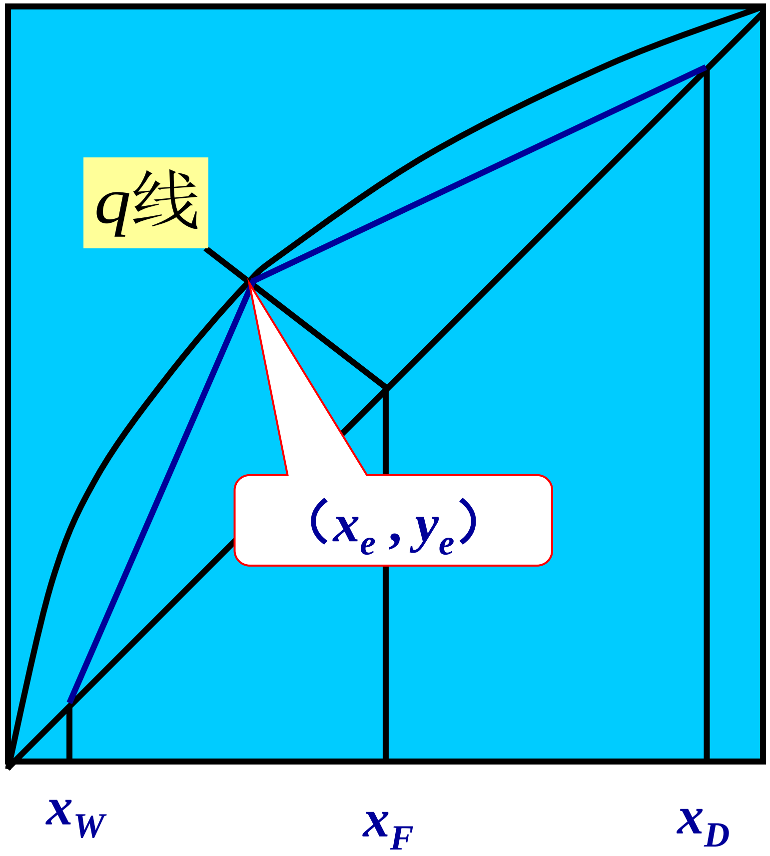
五、设计型计算[139]

（二）回流比的选择

2. 最小回流比

图解法——

恒浓区出现在进料处



第五节 双组分连续精馏塔的计算

五、设计型计算[140]

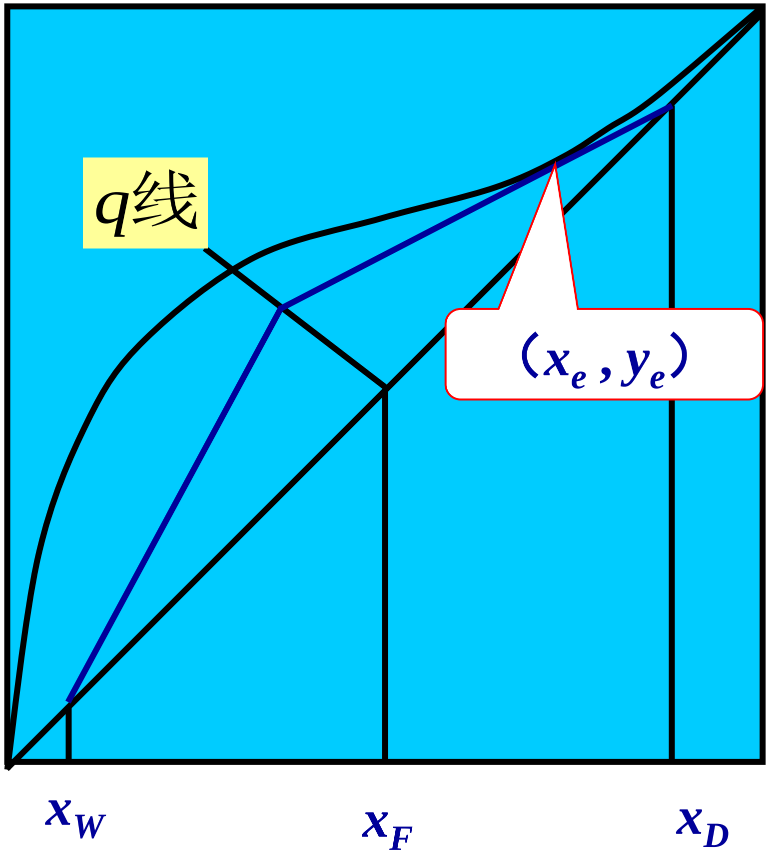
（二）回流比的选择

2. 最小回流比

图解法——

恒浓区出现在精馏段

（正偏差物系）



第五节 双组分连续精馏塔的计算

五、设计型计算

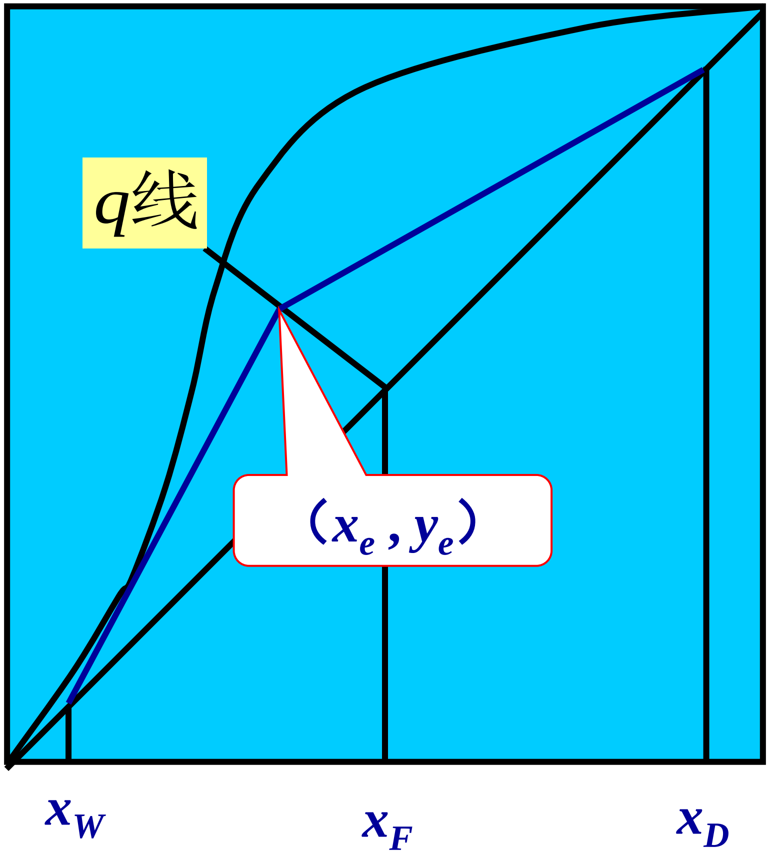
（二）回流比的选择

2. 最小回流比

图解法——

恒浓区出现在提馏段

（负偏差物系）



第五节 双组分连续精馏塔的计算

五、设计型计算

（二）回流比的选择

2. 最小回流比

解析法——

underwood方程

***a*恒定的物系（理想物系）**

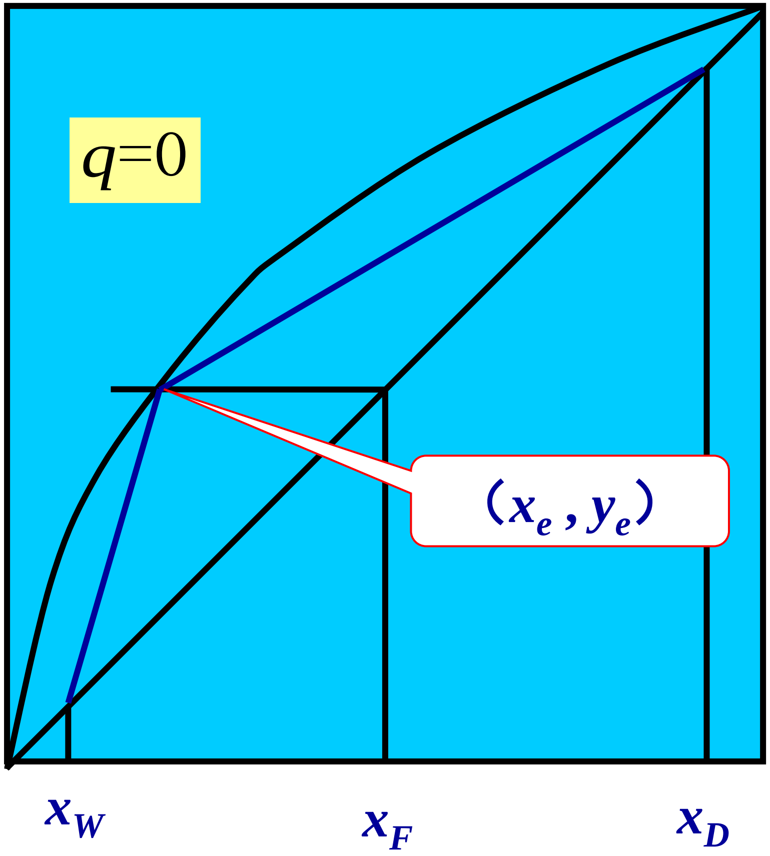
泡点进料： $x_e = x_F \qquad y_e = \dfrac{\alpha x_e}{1+(\alpha-1)x_e}$

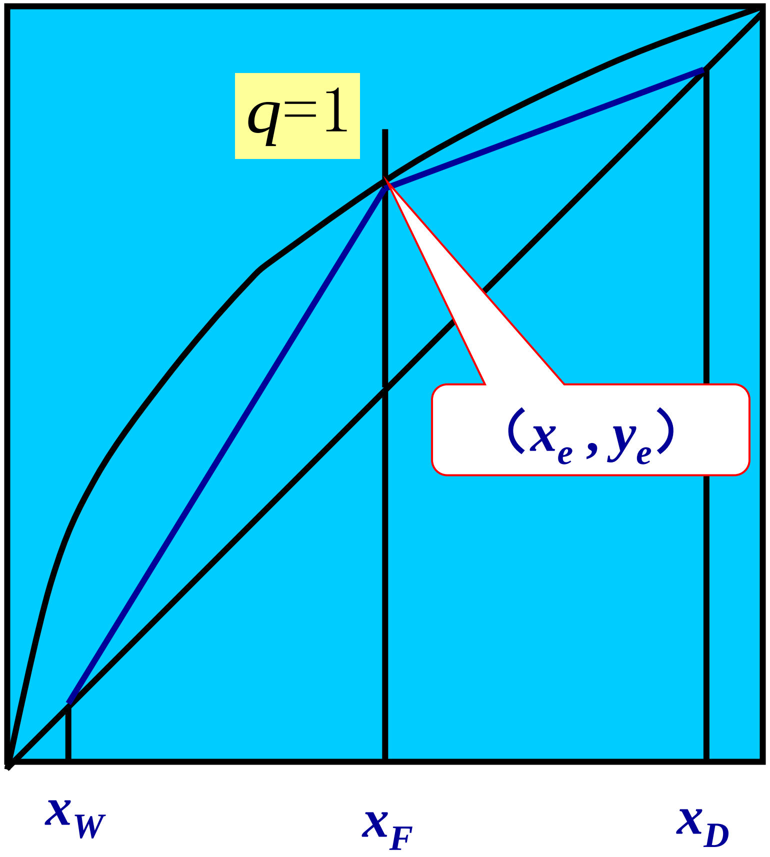
$$R_{\min} = \frac{1}{\alpha-1}\left[\frac{x_D}{x_F} - \frac{\alpha(1-x_D)}{1-x_F}\right]$$

露点进料： $y_e = y_F(x_F) \qquad x_e = \dfrac{y_e}{\alpha-(\alpha-1)y_e}$

$$R_{\min} = \frac{1}{\alpha-1}\left[\frac{\alpha x_D}{y_F} - \frac{1-x_D}{1-x_F}\right] - 1$$

（二）最小回流比



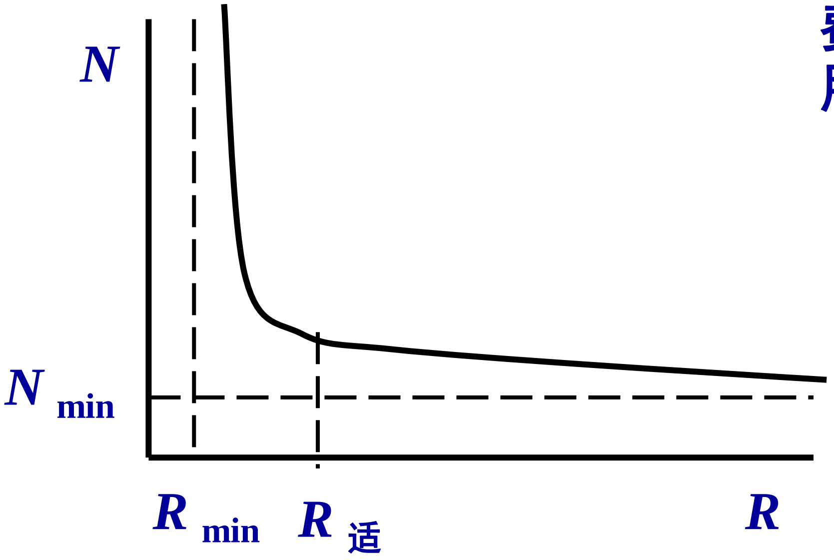


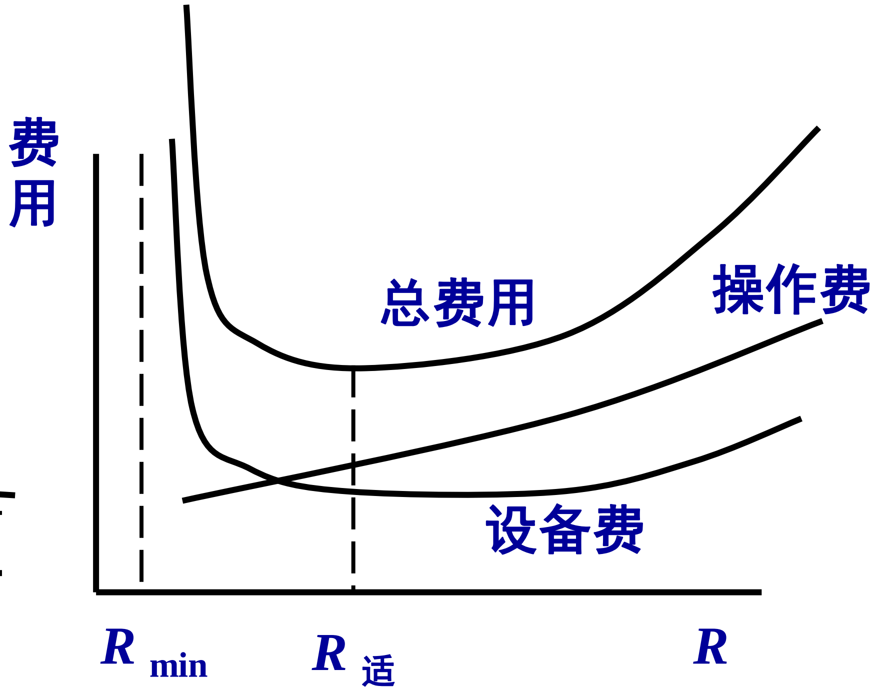
第五节 双组分连续精馏塔的计算

五、设计型计算[140]

（二）回流比的选择

3. 适宜回流比

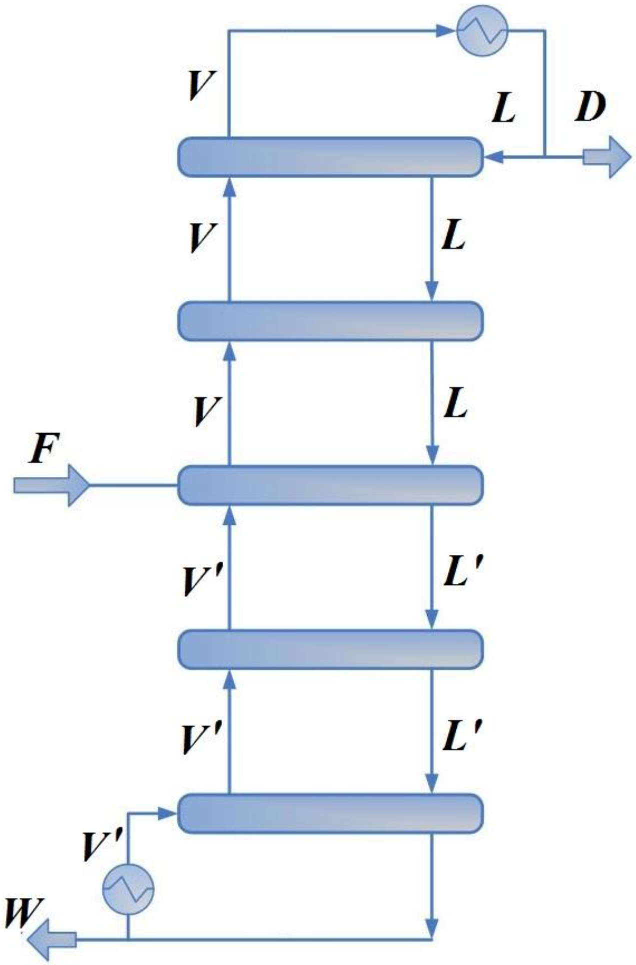




一般适宜回流比取： $R=(1.1\sim2)R_{\min}$

第五节 双组分连续精馏塔的计算

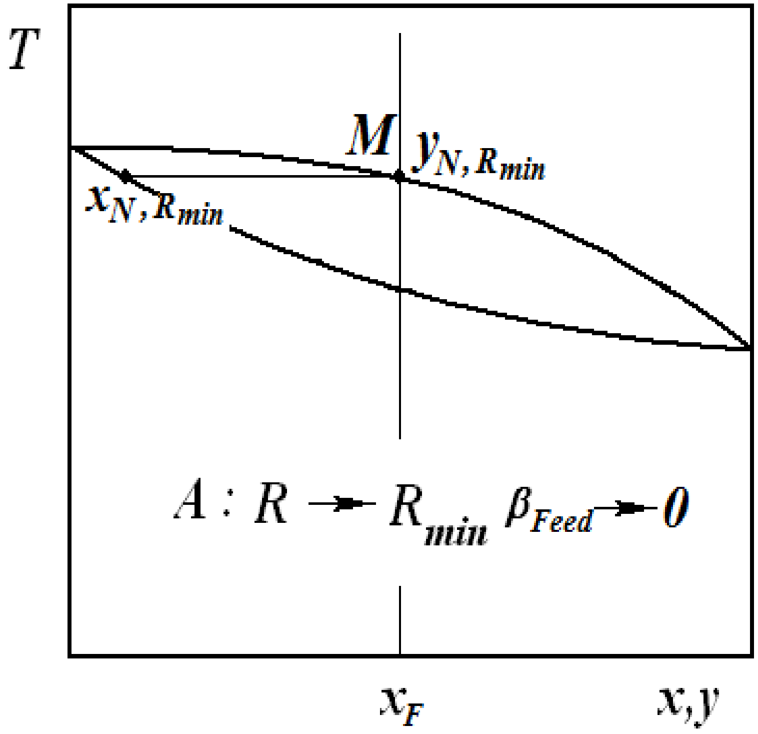
回流比对精馏塔操作的影响



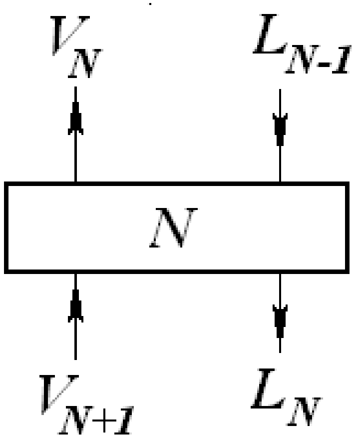
回流的真实含义是为精馏过程提供冷源

第五节 双组分连续精馏塔的计算

回流比对精馏塔操作的影响



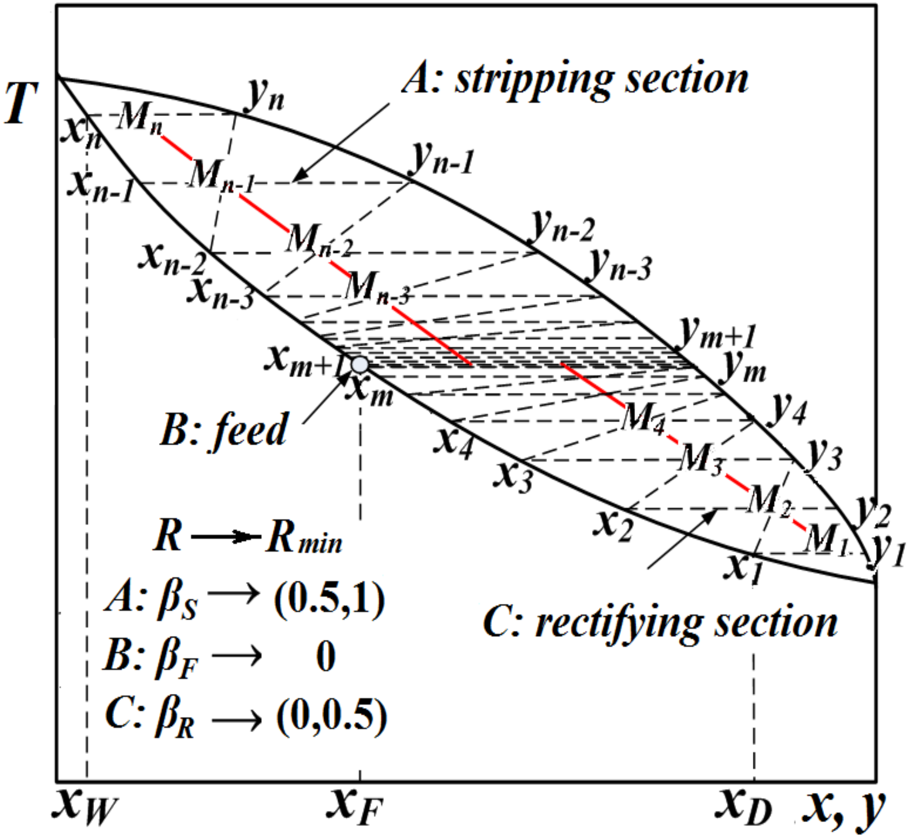
最小回流比



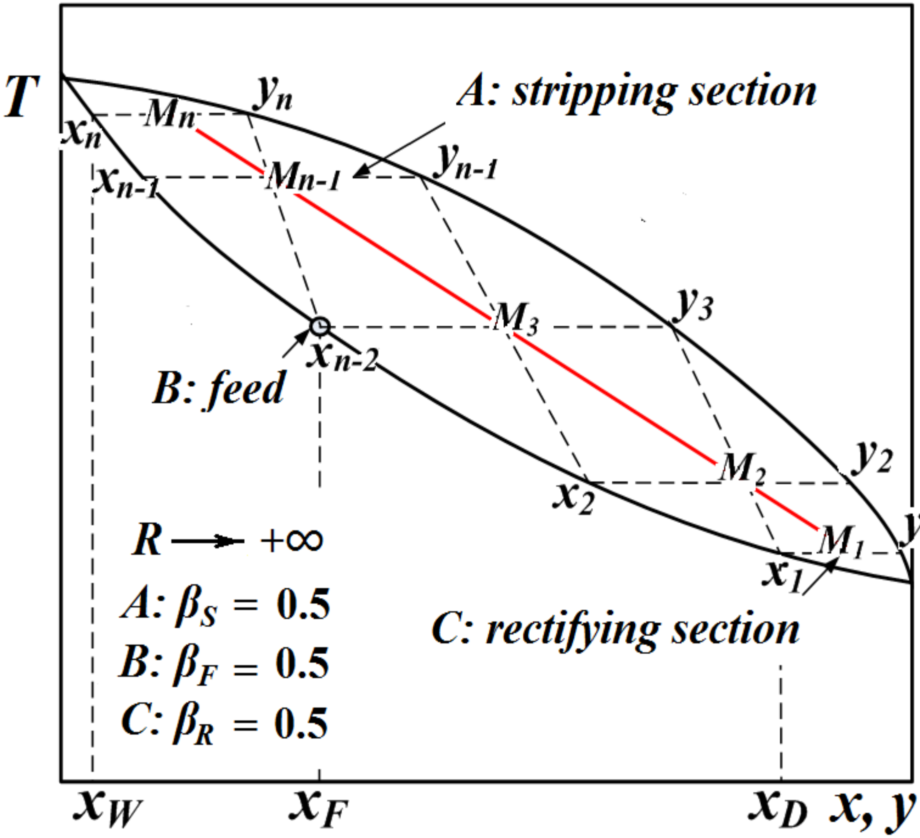
$$\boxed{\beta_N = \frac{L_N}{M_N} = \frac{L_N}{L_N + V_N}}$$

第五节 双组分连续精馏塔的计算

回流比对精馏塔操作的影响



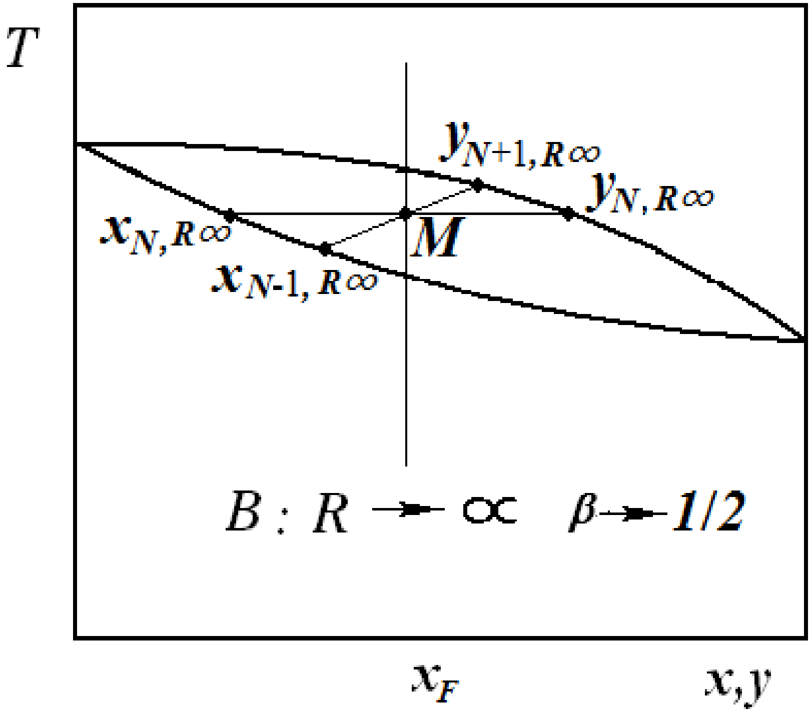
最小回流比



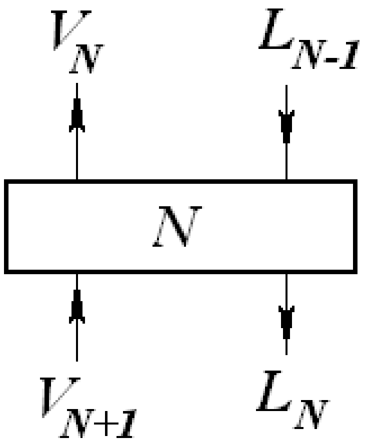
全回流

第五节 双组分连续精馏塔的计算

回流比对精馏塔操作的影响

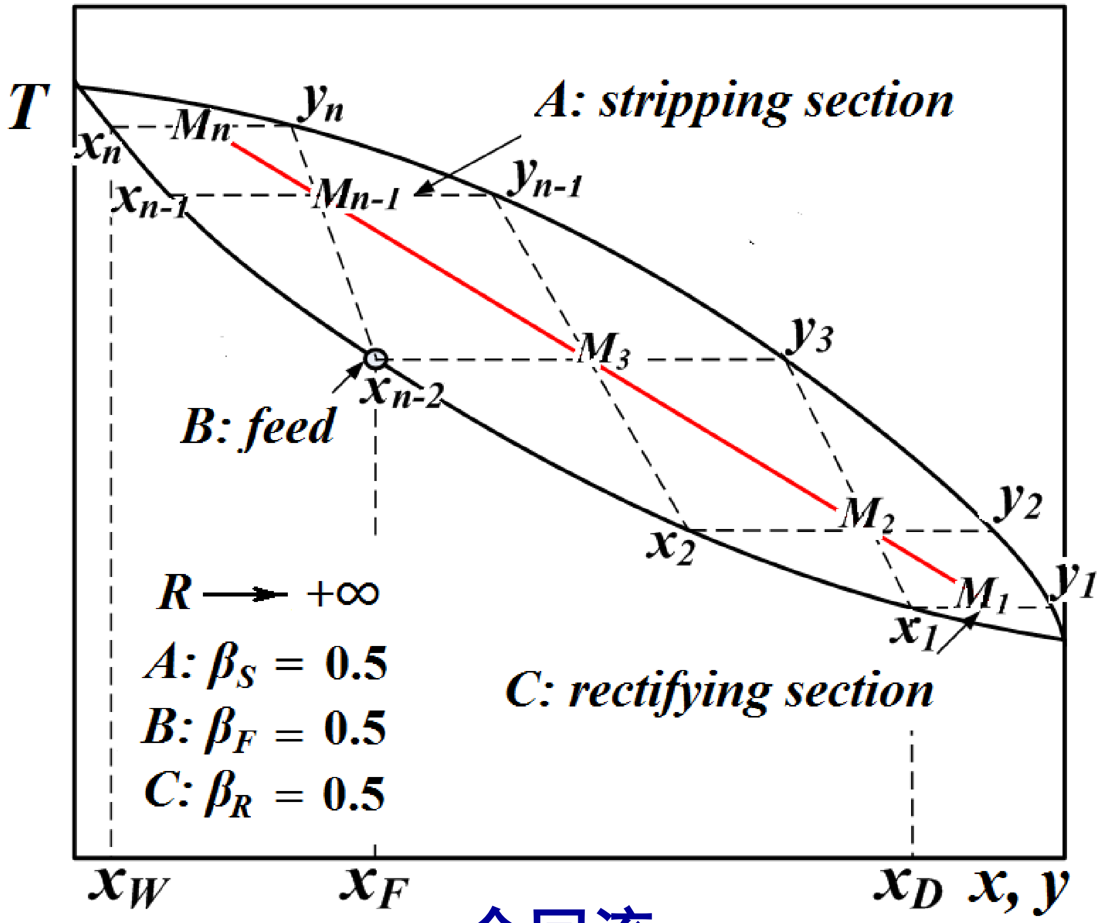


全回流



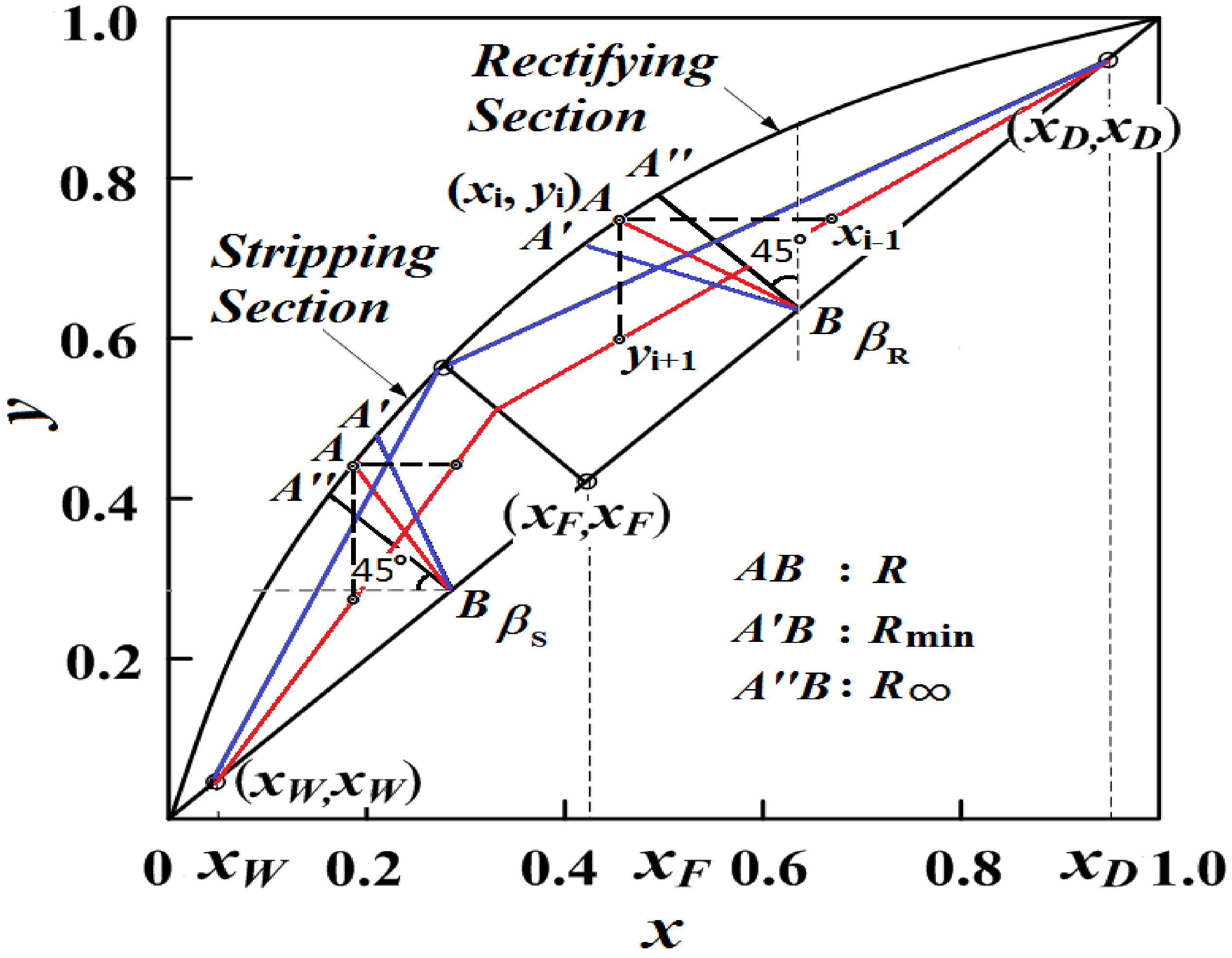
$$\beta_N = \frac{L_N}{M_N} = \frac{L_N}{L_N + V_N}$$

回流比对精馏塔操作的影响



全回流

第五节 双组分连续精馏塔的计算



第五节 双组分连续精馏塔的计算

五、设计型计算[147]

（三）简捷法-Gilliland法

计算步骤：

① 计算R_{min}；

② 计算 N_{min}(包括再沸器)；

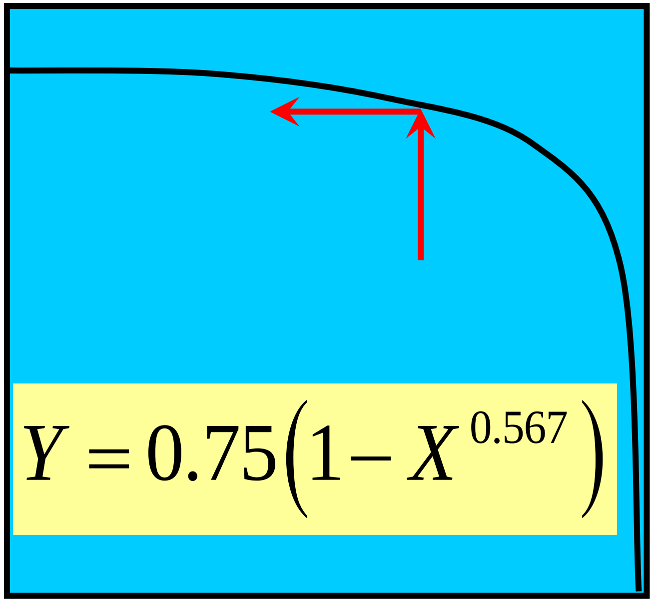
③ 计算$X=(R-R_{min})/(R+1)$

$Y=(N-N_{min})/(N+1)$ ；

④ 查Gilliland图，得Y，求N;

⑤ 确定进料板位置。

$$Y=\frac{N-N_{min}}{N+1}$$



$$Y=0.75\left(1-X^{0.567}\right)$$

$$X=\frac{R-R_{min}}{R+1}$$

第五节 双组分连续精馏塔的计算

1. Gilliland[3-6]图：

考察了61个实际工况下的数据，适用于：Number of components: 2~11，*q*: 0.28~1.42，Pressure: vacuum~4.14MPa，*α*: 1.11~4.05，$R_{\min}$: 0.53~9.09，$N_{\min}$: 3.4~60.3的情况。

优点：工程数据。

缺点：数据点只有61个，数据分布过于集中，缺乏接近最小回流比或全回流的点。

第五节 双组分连续精馏塔的计算

2. Molokanov[13]关联：见式（4）。

$$Y=1-\exp\left(\frac{1+54.4X}{11+117.2X}\cdot\frac{X-1}{\sqrt{X}}\right)$$

缺点：精度尚可，但方程复杂，当X=0时不能用。

3. Eduljee [14]关联：见式（5）。

$$Y=0.75\left(1-X^{0.567}\right)$$

缺点：当X=0时，Y=0.75。

【提问】

回流比的选择

某连续精馏塔中，若精馏段操作线方程的截距等于零，则：

（１）回流比等于___∞___；

（２）馏出液量等于___0___；

（３）操作线斜率等于___1___；

（４）理论塔板数___最少___。

（石油大学2003年）

第九章　蒸馏

CONTENT

05 设计型计算

第五节 双组分连续精馏塔的计算

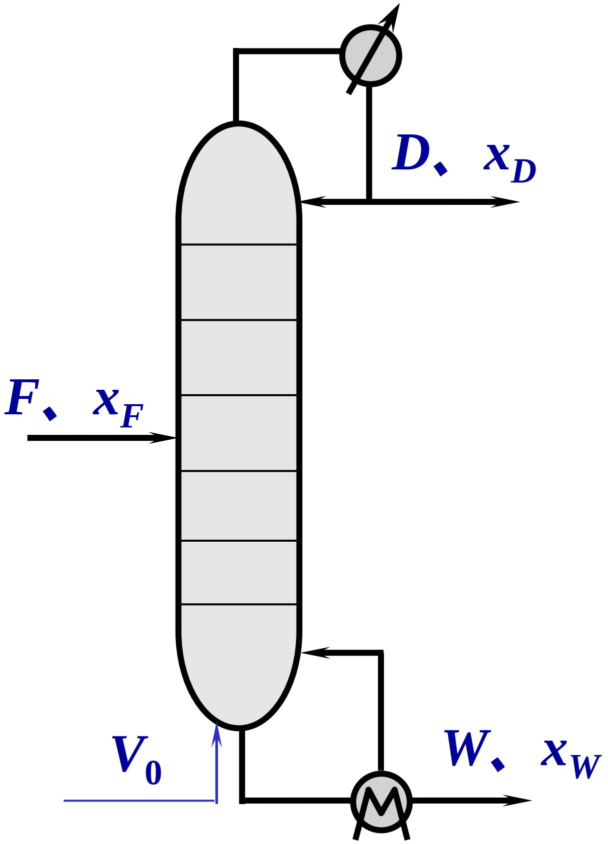
五、设计型计算[142]

（三）特殊情况理论板数的计算

1. 直接水蒸汽加热

用于：

双组分混合物中的难挥发组分为水，作为热源。



第五节 双组分连续精馏塔的计算

五、设计型计算[142]

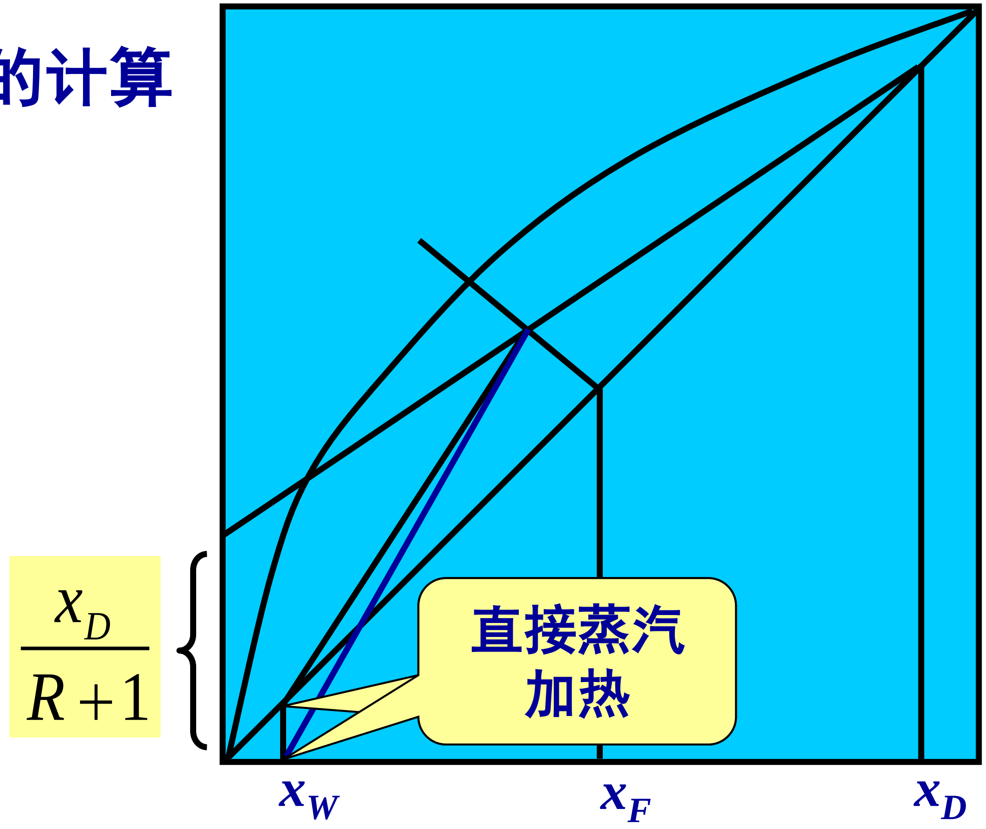
（三）特殊情况理论板数的计算

1. 直接水蒸汽加热

提馏段操作线方程：

$$y'_{m+1} = \frac{L'}{V_0} x'_m - \frac{W x_W}{V_0}$$

V_0：直接加热水蒸汽量

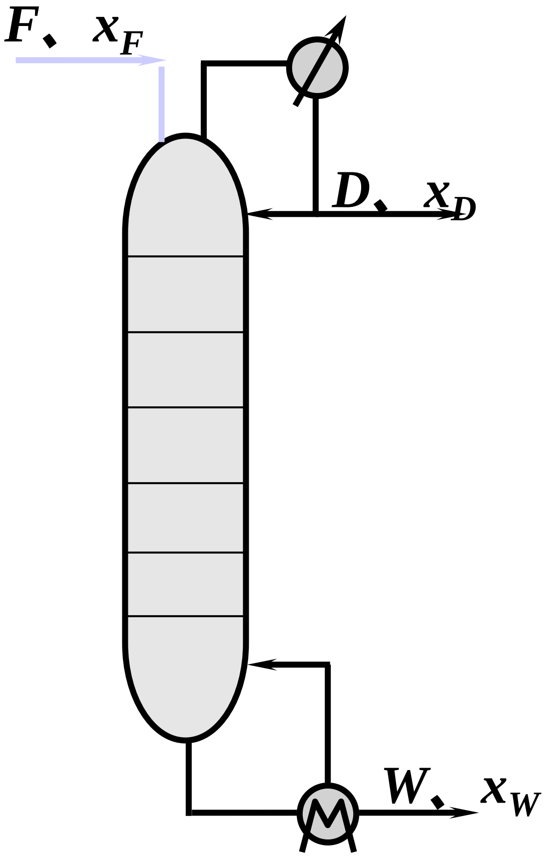


第五节 双组分连续精馏塔的计算

五、设计型计算

（三）特殊情况理论板数的计算

2. 回收塔



用于：

回收稀溶液中易挥发组分，对馏出液的浓度要求不高。

F : 提供液相（类似回流）

第五节 双组分连续精馏塔的计算

（三）特殊情况理论板数的计算

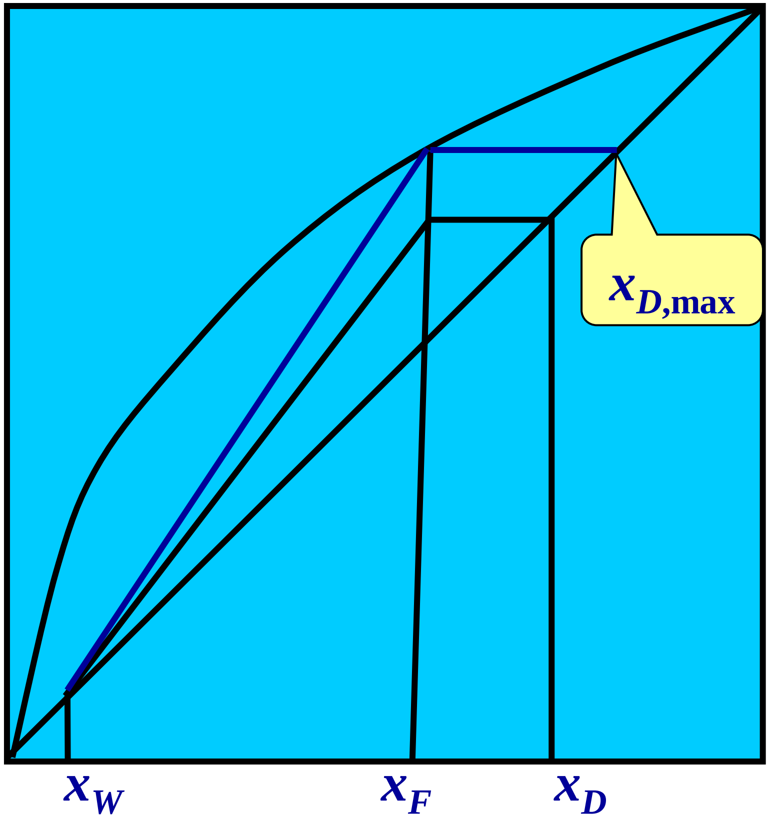
2. 回收塔

操作线方程：

$$y'_{m+1}=\frac{F}{D}x'_m-\frac{Wx_W}{D}$$

进料作为内循环液相，

内循环蒸汽为塔顶产品。



第五节 双组分连续精馏塔的计算

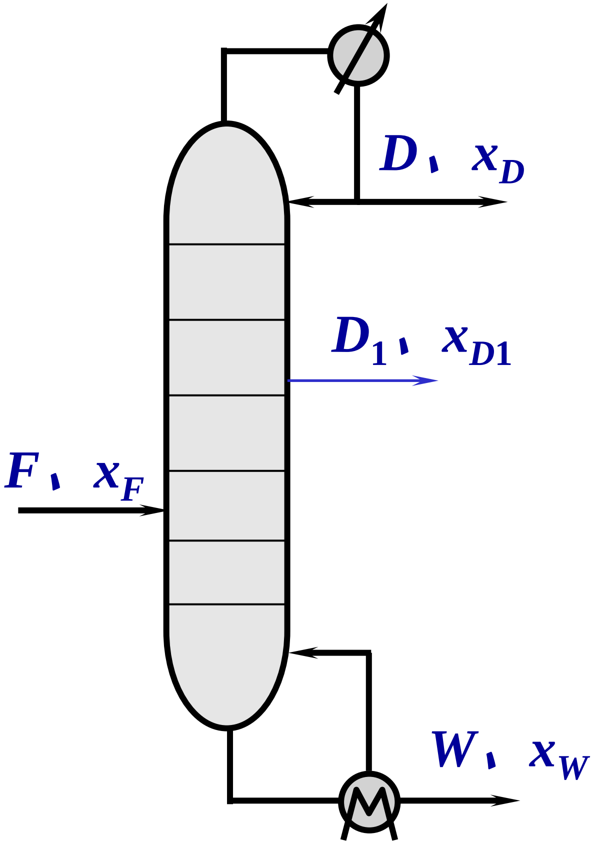
（三）特殊情况理论板数的计算

3. 多侧线出料

用于：

由一个塔得到组成不同的多个产品。

D_1 : 饱和液相抽出



第五节 双组分连续精馏塔的计算

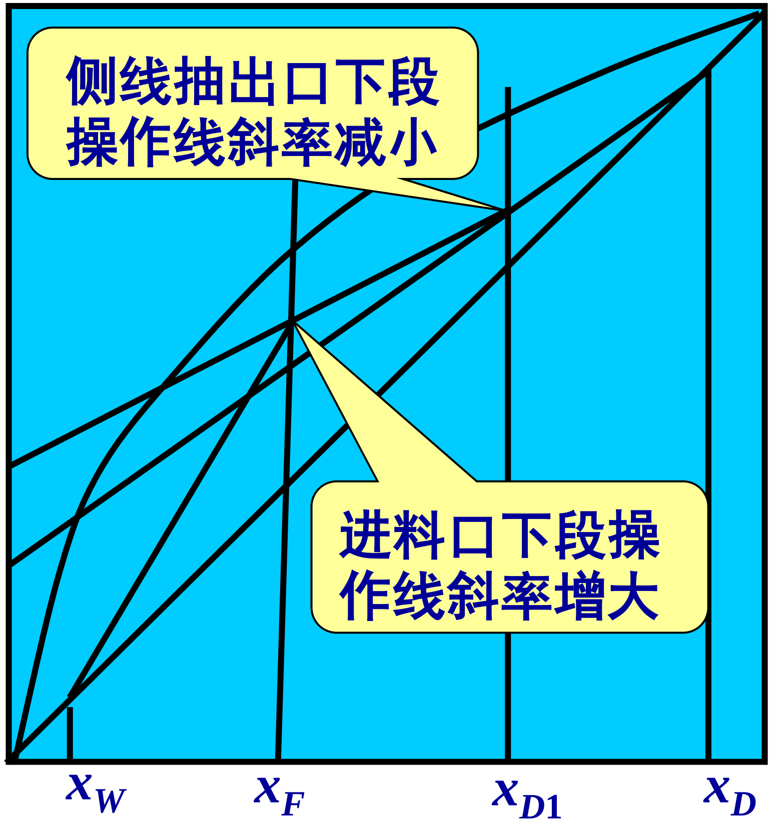
（三）特殊情况理论板数的计算

3. 多侧线出料

中间段操作线方程：

$$y_{S+1}=\frac{L'}{V'}x_S+\frac{Dx_D+D_1x_{D1}}{V'}$$

$$L'=L-D_1,\qquad V'=V$$



第五节 双组分连续精馏塔的计算

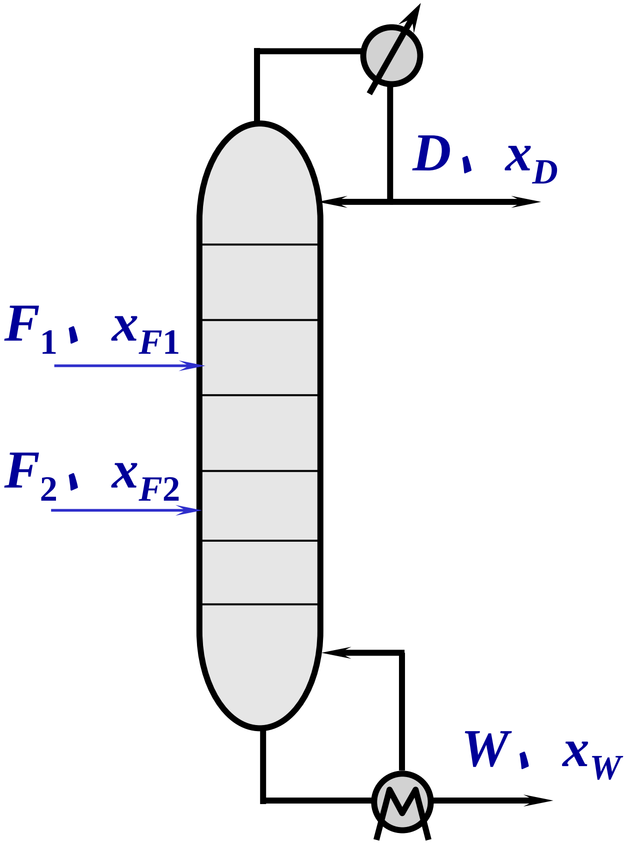
五、设计型计算[144]

（三）特殊情况理论板数的计算

4. 多股进料

用于：

分离组分相同、但组成不同的几股进料。



第五节 双组分连续精馏塔的计算

五、设计型计算[144]

（三）特殊情况理论板数的计算

4. 多股进料

两进料中间段操作线方程：

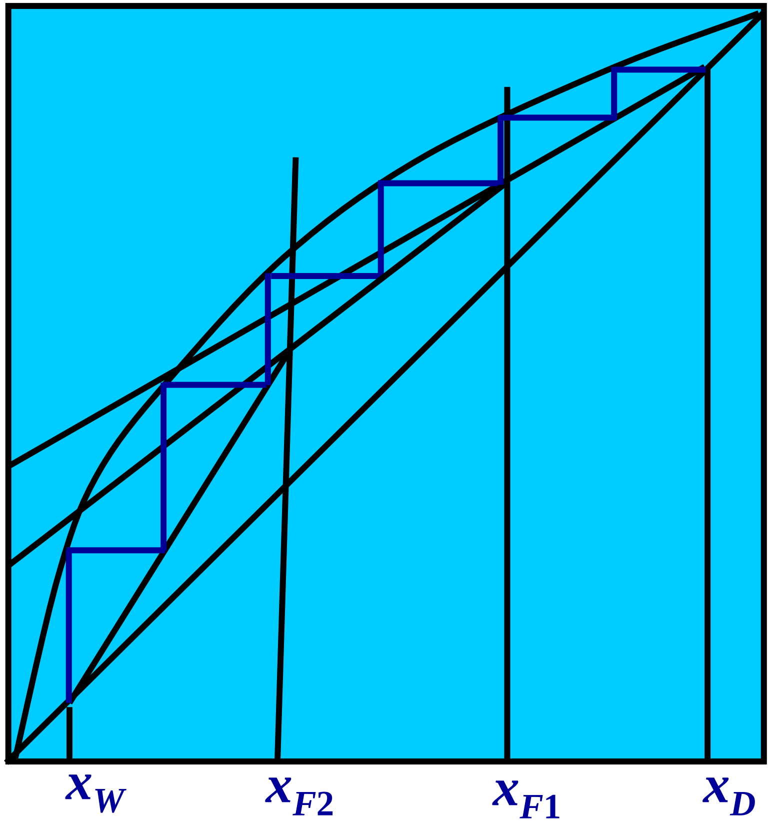
$$y_{S+1} = \frac{L'}{V'} x_S + \frac{D x_D - F_1 x_{F1}}{V'}$$

$$L' = L + q_1 F_1,$$

$$V' = V - (1 - q_1) F$$

$$L'' = L + q_1 F + q_2 F_2,$$

$$V'' = V - (1 - q_1) F_1 - (1 - q_2) F_2$$



第五节 双组分连续精馏塔的计算

五、设计型计算[144]

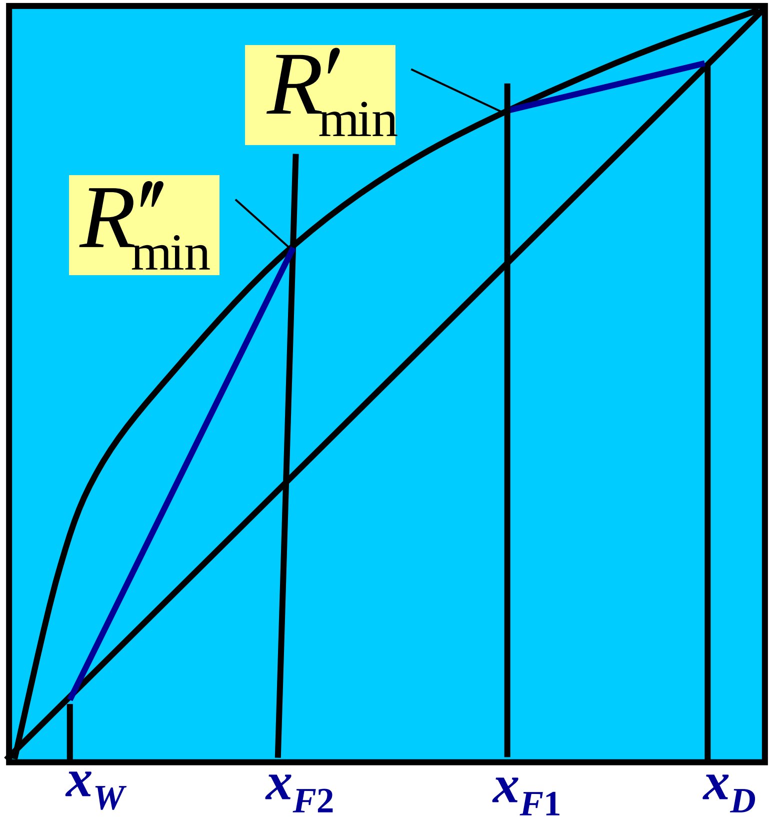
（三）特殊情况理论板数的计算

4. 多股进料

最小回流比：

$$R_{\min} = \max\left\{R'_{\min}, R''_{\min}\right\}$$

将所有可能的最小回流比求出，取其最大值。



本次课内容及要求

第四节 双组分连续精馏塔的计算

四、进料热状况

五、设计型计算

（一）理论板数的计算

（二）回流比的选择

（三）特殊情况理论板数的计算

练习：补充题

预习：精馏操作分析[141]、塔板效率[128]

【补充题1】

有苯—甲苯混合物，含苯0.4，流量1000 kmol/h，在一常压精馏塔内进行分离。要求塔顶馏出液中含苯0.9（以上均为摩尔分率）。苯的回收率不低于90%，泡点状态进料，泡点回流。取回流比为最小回流比的1.5倍，相对挥发度为2.5。求：

① 塔顶产品量；

② 塔底产品量及组成；

③ 最小回流比；

④ 精馏段及提馏段操作线方程；

⑤ 理论板数及进料位置。

设计型计算

【提问】

一、 精馏设计时，F、x_F、D、x_D、R、a 一定，若进料温度降低，则提馏段液汽比L'/V'______，所需理论板数N_T______。

二、精馏设计时，若F、x_F、x_D、x_W、a、V'均为定值，将进料热状态从$q=1$变为$q>1$，则设计时所需的理论板数______。

【结论】

一般而言，在热耗不变的情况下，热量应尽可能在塔底输入，使所产生的汽相回流能在全塔中发挥作用；而冷却量应尽可能施加于塔顶，使所产生的液体回流能经过全塔而发挥最大的效能。