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Distillation Column Efficiency

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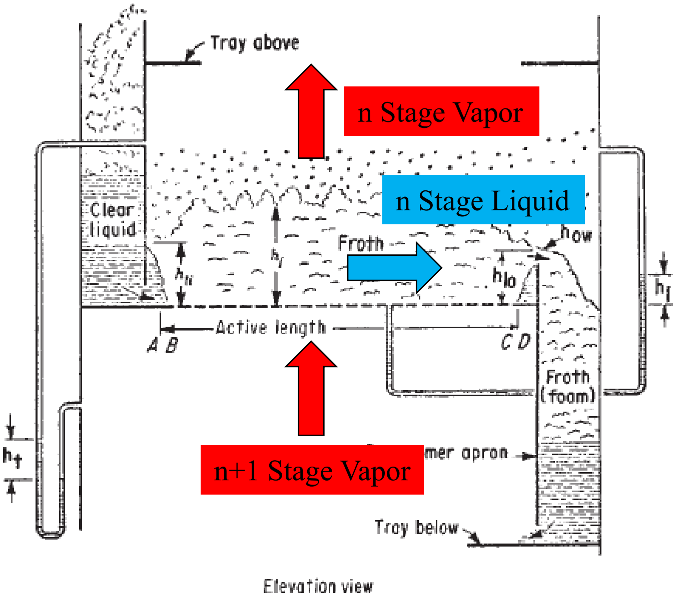
Introduction

- In the design of a distillation column, it is necessary to determine the column diameter and the column height for economic considerations. When determining the column height, the required theoretical number of stages is generally determined from the results of vapor-liquid equilibrium calculations, but in order to determine the actual column height, it is necessary to determine the column efficiency and the stage efficiency.
- Efforts have been made to estimate this efficiency empirically or theoretically (semi- theoretically), but highly accurate correlations have not yet been established.
- Here, the main approaches in considering the efficiency of tray columns will be summarized and a brief comparison will be made with actually reported examples.

Stage Efficiency

- In the case of a tray-type distillation column, vapor-liquid contact occurs on the tray, and heat and mass transfer occur.
- However, since the contact time of the vapor and liquid is short, the number of stages required is greater than the theoretical number of stages obtained by assuming that equilibrium is reached.
- A measure of the deviation from such vapor-liquid equilibrium is the stage efficiency (plate efficiency, tray efficiency), and the following three types are generally used.



1) Overall stage efficiency (column efficiency)
2) Point efficiency
3) Murphree efficiency

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Overall Stage Efficiency (Column Efficiency)

- Column efficiency (EO) is expressed as the ratio of the number of theoretical stages to the number of actual stages, and if this value is known, the number of actual stages can be determined.

$$E_O = \frac{\text{Number of Theoretical Stages}}{\text{Actual Number of Stages}}$$

- Although it is extremely convenient for practical use and widely employed, it is in fact given empirically without any theoretical basis.
- The column efficiency of industrial tray columns is said to be about 60 to 90% for light hydrocarbons and water systems, and about 10 to 20% for gas absorption and diffusion.
- In particular, as a rough guideline, in the case of bubble-cap columns, the following values have been considered: 80% for high pressure columns, 60% for normal pressure columns, and 40% for vacuum columns.
- Well known empirical correlations of column efficiency include Drickamer & Bradford (1943), O'Connell (1946), Lockhart and Leggett (1958), and they enable to easily predict the efficiency with few parameters.

Column Efficiency Estimation
1: Drickamer & Bradford Correlation

- Reported as a function of viscosity alone on the column efficiency of hydrocarbon-based fractionation on an industrial scale. The viscosity used for calculation uses the molar average viscosity of the feed liquid at the average of the temperatures at the top and the bottom of the column.
- It is a graph correlated with bubble-cap column data mainly for propane, butane and pentane, so caution is required when using systems other than hydrocarbons. (However, it applies relatively well to the distillation of acetic acid, alcohols, and the like, and hydrocarbon absorption columns.)

$$\boxed{\begin{aligned} &E_O = 0.17 - 0.616 \times \log_{10}(\mu) \\ &\mu : \text{Liquid Viscosity } [\text{cP}] \end{aligned}}$$

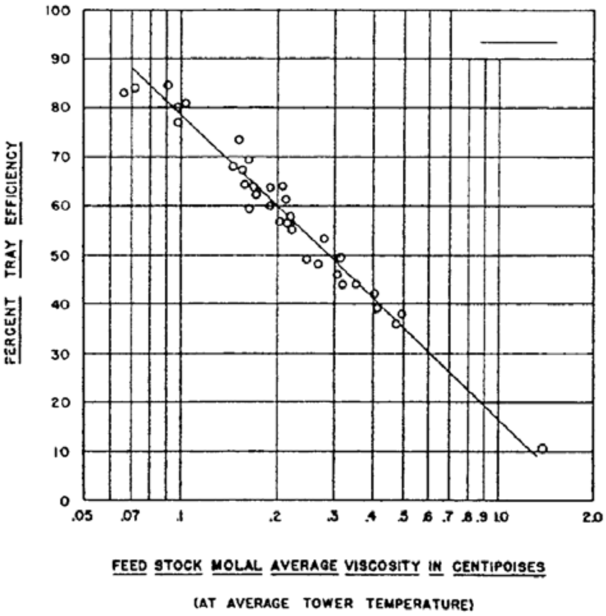

FIG. 14-46 The Drickamer and Bradford tray efficiency correlation for refinery towers. To convert centipoise to pascal-seconds, multiply by 0.0001. [*From Drickamer and Bradford,* Trans. Am. Inst. Chem. Eng. **39**, 319 *(1943). Reprinted courtesy of the AIChE.*]

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Column Efficiency Estimation
2: O'Connell's Correlation

- O'Connell added a correction to Bradford's correlation, as it was pointed out that the efficiency is too high for highly volatile hydrocarbons.
- O'Connell expressed efficiency as a function of relative volatility and feed viscosity. Both values are calculated using the average of the top and bottom temperatures. For the bottom, strictly speaking, the reboiler temperature is used.
- Non-hydrocarbon data are also reflected, and it is one of the most used methods for determining column efficiency.

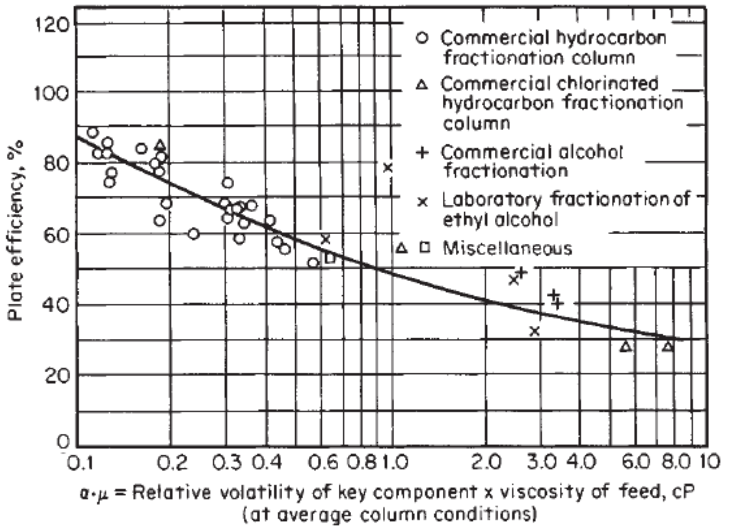

FIG. 14-36 O'Connell correlation for overall column efficiency E_{oc} for distillation. To convert centipoises to pascal-seconds, multiply by 10^{-3}. [*O'Connell,* Trans. Am. Inst. Chem. Eng., *42, 741 (1946).*]

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Column Efficiency Estimation
3: Lockhart & Leggett Correction

- O'Connell's correlation was obtained for columns with a liquid flow path length of 1 m or less (2 to 3 ft) on the tray, but it is known that the column efficiency improves as the liquid flow path length increases. In consideration of this, Lockhart et al. added a correction value to the O'Connell correlation corresponding to the liquid flow path length.

$$\boxed{\begin{aligned} &E_O = 0.492(\alpha \cdot \mu)^{-0.245} \\ &\alpha : \text{Relative Volatility} \\ &\mu : \text{Liquid Viscosity } [\text{cP}] \end{aligned}}$$

The applicable range is $0.1 \le (\alpha \times \mu) \le 1.0$

Liquid Flow Path Length [m]	Percentage to Add to Eo of Figure %
1.0	0
1.2	10
1.5	15
1.8	20
2.4	23
3.0	25
4.6	27

Note: The column efficiency is affected by various factors such as the accuracy of the vapor-liquid equilibrium correlation, the type and nature of fluid, the column diameter, the tray shape, and the operating conditions. For this reason, O'Connell's correlation (Lockhart's correction) is rarely used in actual design. However, grasping the concept of the overall efficiency has a great significance in this type of investigation.

"Shinpan Jouryuu no Riron to Keisan Kougakutosho", *in Japanese*: "Distillation Theory and Computational Engineering New Edition", p481

Stage Efficiency Estimation: Point Efficiency

- It is not possible to directly express the differences in components and efficiencies on each tray in terms of column efficiency. Thus, the efficiency considered for any one point on a tray is expressed as the point efficiency (E_{OG}), which is usually defined based on the vapor composition.
- The point efficiency (E_{OG}) is expressed as the ratio of the change in composition assuming an equilibrium state to the change in the actual composition.

(i) Point Efficiency

$$\boxed{E_{OG,i} = \frac{y_{n,i} - y_{n+1,i}}{y_{n,i}^{*} - y_{n+1,i}}}$$

Where, $E_{OG,i}$ is the vapor phase Murphree point efficiency of component i in the nth stage, and $y_{n,i}$ and $y_{n+1,i}$ are the molar fractions of the vapor generated from the nth stage and of the low boiling point component i in the vapor flowing into the nth stage, and $y_{n,i}^{*}$ is the molar fraction of component i in the vapor in equilibrium with the liquid of the n^{th} stage.

"Kagaku Kougaku Binran", *in Japanese*: "Chemical Engineering Handbook", revised 6th ed., p529

Stage Efficiency Estimation: Murphree Stage Efficiency

- The stage efficiency (E_{MV}), which is the ratio of the actual vapor concentration fraction as it passes through the tray to the concentration fraction when assuming an equilibrium stage, makes it possible to reflect vapor and liquid mixing conditions and various concentration differences for each location.

(ii) Stage Efficiency (Murphree Efficiency)

$$\boxed{E_{MV,i} = \frac{y_{n,i} - y_{n+1,i}}{\left(y_{n,i}^{*}\right)_{out} - y_{n+1,i}}}$$

Where, $E_{MV,i}$ is the Murphree vapor phase point efficiency [-] of component *i* in the nth stage, and $(y_{n,i}^{*})_{\mathrm{out}}$ is the molar fraction of the component *i* in the vapor in equilibrium with the liquid flowing out from the *n*th stage.

"Kagaku Kougaku Binran", *in Japanese*: "Chemical Engineering Handbook", revised 6th ed., p529

- The liquid flowing on the tray is almost homogeneous in the vertical direction due to the stirring effect of the steam, but is not homogeneous in the horizontal direction, and the point efficiency and the Murphree stage efficiency differ as the column inner diameter increases. The two equations almost match when the column diameter is smaller than 0.5 m (when the liquid is completely mixed).

Stage Efficiency Estimation: Murphree Stage Efficiency

- In plug flow conditions, the column efficiency and the Murphree efficiency have the following relationship:

$$\boxed{E_O = \frac{\log_{10}\left\{1 + E_{MV}\left(m \cdot V/L - 1\right)\right\}}{\log_{10}\left(m \cdot V/L\right)}}$$

m : Slope of Vapor-Liquid Equilibrium Line

V/L : Vapor and Liquid Molar Flow Rate

Note: The actual liquid flow is an intermediate state between perfect mixing and plug flow, and the predictive formula was proposed by AIChE's research.

Efficiency of Tray Columns – Measured Values (Perry's Handbook)

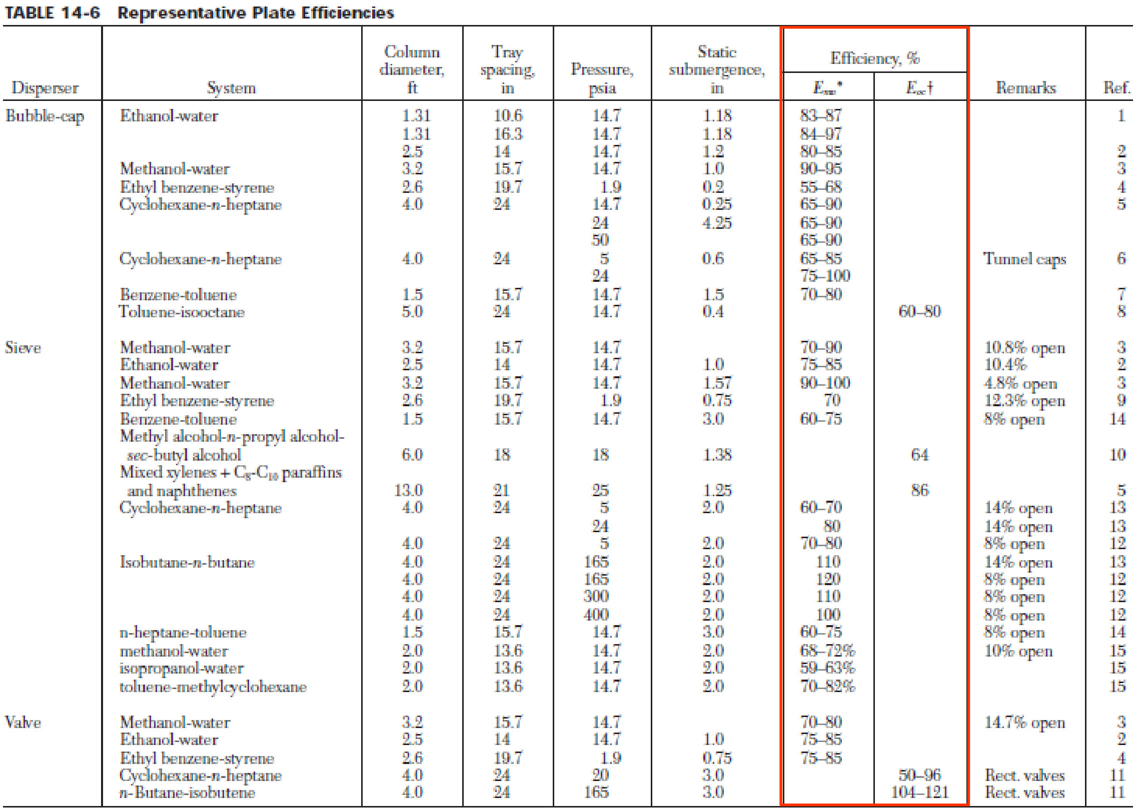

TABLE 14-6 Representative Plate Efficiencies

Disperser	System	Column diameter, ft	Tray spacing, in	Pressure, psia	Static submergence, in	Efficiency, % E_{mv}*	Efficiency, % E_{oc}†	Remarks	Ref.
Bubble-cap	Ethanol-water	1.31	10.6	14.7	1.18	83–87			1
		1.31	16.3	14.7	1.18	84–97			
		2.5	14	14.7	1.2	80–85			2
	Methanol-water	3.2	15.7	14.7	1.0	90–95			3
	Ethyl benzene-styrene	2.6	19.7	1.9	0.2	55–68			4
	Cyclohexane-*n*-heptane	4.0	24	14.7	0.25	65–90			5
				24	4.25	65–90			
				50		65–90			
	Cyclohexane-*n*-heptane	4.0	24	5	0.6	65–85		Tunnel caps	6
				24		75–100			
	Benzene-toluene	1.5	15.7	14.7	1.5	70–80			7
	Toluene-isooctane	5.0	24	14.7	0.4		60–80		8
Sieve	Methanol-water	3.2	15.7	14.7		70–90		10.8% open	3
	Ethanol-water	2.5	14	14.7	1.0	75–85		10.4%	2
	Methanol-water	3.2	15.7	14.7	1.57	90–100		4.8% open	3
	Ethyl benzene-styrene	2.6	19.7	1.9	0.75	70		12.3% open	9
	Benzene-toluene	1.5	15.7	14.7	3.0	60–75		8% open	14
	Methyl alcohol-*n*-propyl alcohol-*sec*-butyl alcohol	6.0	18	18	1.38		64		10
	Mixed xylenes + C_8-C_{10} paraffins and naphthenes	13.0	21	25	1.25		86		5
	Cyclohexane-*n*-heptane	4.0	24	5	2.0	60–70		14% open	13
				24		80		14% open	13
		4.0	24	5	2.0	70–80		8% open	12
	Isobutane-*n*-butane	4.0	24	165	2.0	110		14% open	13
		4.0	24	165	2.0	120		8% open	12
		4.0	24	300	2.0	110		8% open	12
		4.0	24	400	2.0	100		8% open	12
	n-heptane-toluene	1.5	15.7	14.7	3.0	60–75		8% open	14
	methanol-water	2.0	13.6	14.7	2.0	68–72%		10% open	15
	isopropanol-water	2.0	13.6	14.7	2.0	59–63%			15
	toluene-methylcyclohexane	2.0	13.6	14.7	2.0	70–82%			15
Valve	Methanol-water	3.2	15.7	14.7		70–80		14.7% open	3
	Ethanol-water	2.5	14	14.7	1.0	75–85			2
	Ethyl benzene-styrene	2.6	19.7	1.9	0.75	75–85			4
	Cyclohexane-*n*-heptane	4.0	24	20	3.0		50–96	Rect. valves	11
	n-Butane-isobutene	4.0	24	165	3.0		104–121	Rect. valves	11

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Column Efficiency Comparisons

- The results of the comparison with the measured values are summarized in the table using the Drickamer & Bradford and the O'Connell correlations for systems for which the column efficiency is measured. For the calculation of vapor-liquid equilibrium, calculations were carried out using Aspen Plus, which is a general-purpose simulator, by using an equimolar boiling point liquid of each component as the feed, and by setting the purity and the recovery ratio of each component as 99 mol%. In addition, by definition the key components were used for the calculation of the relative volatilities.

System	Tray type	Column Diameter	Stage Interval [m]	Pressure [ATM]	Column Efficiency [%]	Viscosity [cP]	Relative Volatility	D&B [%]	O'Con [%]
Toluene-*iso* octane	Bubble-cap	1.5	0.6	1	60-80	0.237	1.49	55.52	65.00
Methylalcohol / *n* -propyl alcohol /*sec* -butyl alcohol	Sieve tray	1.8	0.5	1.22	64	0.472	4.03	37.09	42.00
Mixed xylenes/ C8-C10 paraffins/ naphthens	Sieve tray	4	0.5	1.7	86	0.224	1.37	57.02	66.00

Drickamer & Bradford's correlation has large errors because it derives the column efficiency using viscosity alone. In the O'Connell correlation, although the accuracy is slightly improved by taking the relative volatility into consideration, it can be seen that the prediction results remain very much on the safe side.
The O'Connell correlation is described as follows in Perry's Handbook: "The O'Connell correlation was based on data for bubble-cap trays. For sieve and valve trays, its predictions are likely to be slightly conservative."

Reference: Efficiency Change with Vapor Load

- Experiments conducted with Oldershaw columns, conducted in 1982 by FRI (Fractionation Research Inc.), show that the column efficiency changes by nearly 40 to 60% with respect to the vapor load change (Flooding %) in the column. Thus, the quantification of all factors to the stage efficiency is still unclear.
- In order to increase the stage efficiency, it is necessary to keep sufficient contact between vapor and liquid, by either:

1) Increasing contact time
2) Or it is effective to increase the contact area.

Regarding 1), the liquid depth can be increased

Regarding 2), this can be achieved by increasing the vapor velocity and increasing the bubble dispersion.

On the other hand, if the liquid depth is increased, the pressure loss increases, and if the vapor velocity is increased, in addition to the increase in the pressure drop, entrainment will occur more easily (construction costs will increase if the spacing between trays is increased).

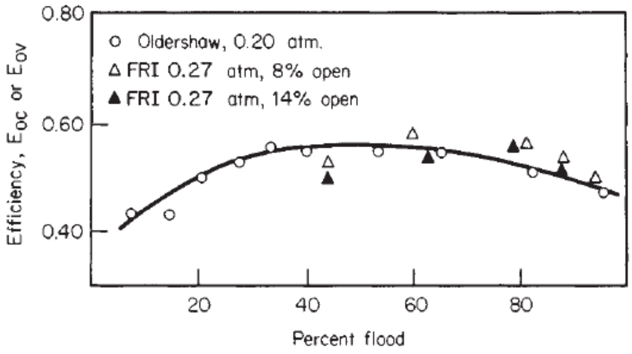

FIG. 14-37 Overall column efficiency of 25-mm Oldershaw column compared with point efficiency of 1.22-m-diameter-sieve sieve-plate column of Fractionation Research, Inc. System = cyclohexane-*n*-heptane. [(*Fair, Null, and Bolles*, Ind. Eng. Chem. Process Des. Dev., **22**, 53 (*1982*).]

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Conclusion

- The number of stages required in a distillation column is greater than the number of theoretical stages because the contact time between vapor and liquid is short. The indicators representing this deviation are the column efficiency and the stage efficiency.
- Empirical correlations and semi-theoretical estimations have been put forward to estimate efficiency, but since various factors such as the accuracy of vapor-liquid equilibrium correlations, the type and nature of fluids, the column diameter, the tray shape, and operating conditions have multiple effects, highly accurate predictions are difficult to obtain, and most are based on past experimental results and the like.
- On the other hand, using O'Connell's correlation, it is possible to predict the efficiency only with a representative viscosity and the geometric average relative volatility, and it seems that it is useful for approximations even though it is imprecise.