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# INFLUENCE OF PHASE RATIO ON PACKING EFFICIENCY IN COLUMNS FOR MASS TRANSFER PROCESSES

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**Abstract** The phase ratio has been found to affect the packing efficiency in packed columns. To account for the effect, a model is set up to correlate the height of a mass transfer unit with the phase ratio with reasonable accuracy. Proposed also is a correlation that allows to predict the efficiency in question at any given liquid-gas ratio using the knowledge of other efficiency values at other liquid-gas ratios.

**Keywords** phase ratio, height of a transfer unit, packings

## 1 INTRODUCTION

Packed columns for thermal separation processes are being adopted nowadays on a wider scale not only in processes but also in ecological engineering. Hence wide extremes in phase loads are encountered. In other words, the columns must be often operated at either very low or very high phase ratios, which depends on the nature of the separation task. Thus, the question of the efficiency of the packings used is of great importance.

## 2 FUNDAMENTAL EQUATIONS FOR DESCRIBING MASS TRANSFER

A mathematical method for the design of packed columns of this nature for absorption, desorption and rectification processes has been proposed at the institute of Thermo-and Fluid-dynamics in the Ruhr-University of Bochum. The method allows reliable theoretical prediction of the column dimensions required for all kinds of random and arranged packings which were investigated. It is based on the results of experimental studies in which the liquid loads were varied between 5 and 50 $m^3 \cdot m^{-2} \cdot h^{-1}$, and now up to $120 m^3 \cdot m^{-2} \cdot h^{-1}$, and the gas loads up to the flood points.

In this method, the height of a packed column required to realise a specific separation task is based on the *HTU-NTU* concept, Eqs.(1)-(3), *i.e.*, the product of the height of a gas side mass transfer unit $HTU_{O,V}$ and the number of these units $NTU_{O,V}$ The number of transfer units is fixed by the task to be performed; and the height of transfer unit, by the physical properties of the system, the two phase loads, and the geometry and texture of the packings

$$H = HTU_{O,V} \quad NTU_{O,V} \tag{1}$$

$$NTU_{O,V} = \int_{y_0}^{y_u} \frac{dy}{y - y_{Ph}} \tag{2}$$

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$$HTU_{\mathrm{O,V}}=HTU_{\mathrm{V}}+\lambda HTU_{\mathrm{L}}=\frac{u_{\mathrm{V}}}{\beta_{\mathrm{V}}a_{\mathrm{Ph}}}+\left(\frac{m_{yx}}{\dot{L}/\dot{V}}\right)\frac{u_{\mathrm{L}}}{\beta_{\mathrm{L}}a_{\mathrm{Ph}}} \tag{3}$$

The height of a transfer unit can be determined for a given system, represented by the slope $m_{yx}$ of the equilibrium line, and for a given liquid-vapor ratio $\dot{L}/\dot{V}$ by calculating the volumetric mass transfer coefficients, $\beta_{\mathrm{L}}a_{\mathrm{Ph}}$ on the liquid and $\beta_{\mathrm{V}}a_{\mathrm{Ph}}$ on the vapour side, with a mass transfer model, Eqs.(4) – (7) already presented by the authors in the previous publications[1-6]

$$\beta_{\mathrm{L}}a_{\mathrm{Ph}}=C_{\mathrm{L}}\left(\frac{g\rho_{\mathrm{L}}}{\eta_{\mathrm{L}}}\right)^{1/6}\left(\frac{D_{\mathrm{L}}}{d_{\mathrm{h}}}\right)^{1/2}a^{2/3}u_{\mathrm{L}}^{1/3}\left(\frac{a_{\mathrm{Ph}}}{a}\right) \tag{4}$$

$$\beta_{\mathrm{V}}a_{\mathrm{Ph}}=C_{\mathrm{V}}\frac{1}{(\varepsilon-h_{\mathrm{L}})^{1/2}}\frac{a^{3/2}}{d_{\mathrm{h}}^{1/2}}D_{\mathrm{V}}\left(\frac{u_{\mathrm{V}}\rho_{\mathrm{V}}}{a\eta_{\mathrm{V}}}\right)^{3/4}\left(\frac{\eta_{\mathrm{V}}}{D_{\mathrm{V}}\rho_{\mathrm{V}}}\right)^{1/3}\left(\frac{a_{\mathrm{Ph}}}{a}\right) \tag{5}$$

$$h_{\mathrm{L}}=\left(12\frac{1}{g}\frac{\eta_{\mathrm{L}}}{\rho_{\mathrm{L}}}u_{\mathrm{L}}a^{2}\right)^{1/3} \tag{6}$$

$$d_{\mathrm{h}}=4\varepsilon/a \tag{7}$$

Thus the influencing variables are the loads $u_{\mathrm{L}}$ and $u_{\mathrm{V}}$, the dynamic viscosities $\eta_{\mathrm{L}}$ and $\eta_{\mathrm{V}}$, the diffusion coefficients $D_{\mathrm{L}}$ and $D_{\mathrm{V}}$, and the densities $\rho_{\mathrm{L}}$ and $\rho_{\mathrm{V}}$ of both phases $\dot{L}$ and $\dot{V}$, the liquid holdup $h_{\mathrm{L}}$ and the dynamic diameter $d_{\mathrm{h}}$ of the packing applied which is specified by its void fraction $\varepsilon$ and the specific area $a$.

The interfacial area $a_{\mathrm{Ph}}$ in the capacity range up to the loading point can be estimated with Eq.(8) for the so-called positive and neutral systems, *i.e.*, if there does not exist a remarkable Marangoni effect. However, if the surface tension $\sigma_{\mathrm{L}}$ in the liquid phase with the local concentration $x$ decreases alongside the flow path, then a reduction in the interfacial surface occurs according to Eq.(9), which indicates the amount of reduction is dependent on the magnitude of the Marangoni number, Eq.(10)

$$\frac{a_{\mathrm{Ph}}}{a}=1.5(ad_{\mathrm{h}})^{-0.5}\left(\frac{u_{\mathrm{L}}d_{\mathrm{h}}}{\nu_{\mathrm{L}}}\right)^{-0.2}\left(\frac{u_{\mathrm{L}}^{2}\rho_{\mathrm{L}}d_{\mathrm{h}}}{\sigma_{\mathrm{L}}}\right)^{0.75}\left(\frac{u_{\mathrm{L}}^{2}}{gd_{\mathrm{h}}}\right)^{-0.45} \tag{8}$$

$$\left(\frac{a_{\mathrm{Ph}}}{a}\right)=\left(\frac{a_{\mathrm{Ph}}}{a}\right)_{\mathrm{Eq.(8)}}(1-2.410^{-4}|Ma_{\mathrm{L}}|^{0.5}) \tag{9}$$

$$Ma_{\mathrm{L}}=\frac{\mathrm{d}\sigma_{\mathrm{L}}}{\mathrm{d}x}\frac{\Delta x}{D_{\mathrm{L}}\eta_{\mathrm{L}}a} \tag{10}$$

The suitability of this model for practical applications was confirmed by systematic experimental investigations and evaluations, comprising more than 3200 results of mass transfer measurements, carried out with 45 different systems and 67 packings with varying sizes, shapes and surface structures, both in dumped and regular arrangements (see Table 1).

**Table 1 Capacity range, test facilities, physical properties of test systems and number of investigated packings and tests**

| | |
|---|---|
| Gas capacity factor, $F_V$, $m^{-1/2} \cdot kg^{1/2} \cdot s^{-1}$ | 0.0029 – 2.773 |
| Liquid load, $u_L$, $m^3 \cdot m^{-2} \cdot h^{-1}$ | 0.2563 – 118.20 |
| Column diameter, $d_s$, m | 0.06 – 1.40 |
| Column height, $H$, m | 0.152 – 3.950 |
| Specific total, surface area, $a$, $m^2 \cdot m^{-3}$ | 55.00 – 711.9 |
| Void fraction, $\varepsilon$, $m^3 \cdot m^{-3}$ | 0.40 – 0.98 |
| Liquid density, $\rho_L$, $kg \cdot m^{-3}$ | 758 – 1237 |
| Liquid viscosity, $\nu_L \times 10^6$, $m^2 \cdot s^{-1}$ | 0.30 – 1.66 |
| Liquid side diffusion coefficient, $D_L \times 10^9$, $m^2 \cdot s^{-1}$ | 1.04 – 6.50 |
| Surface tension, $\sigma_L \times 10^3$, $kg \cdot s^{-2}$ | 17.2 – 74.0 |
| Gas density, $\rho_V$, $kg \cdot m^{-3}$ | 0.066 – 4.929 |
| Gas viscosity, $\nu_V \times 10^6$, $m^2 \cdot s^{-1}$ | 2.2 – 126.2 |
| Gas side diffusion coefficient, $D_V \times 10^6$, $m^2 \cdot s^{-1}$ | 3.7 – 87.4 |
| Schmidt number of liquid, $Sc_L$ | 45 – 1186 |
| Schmidt number of gas, $Sc_V$ | 0.185 – 2.122 |
| Number of investigated packings | 67 |
| Number of measurements for absorption and desorption | 2605 |
| Number of measurements for rectification | 665 |
| Investigated systems for absorption and desorption | 31 |
| Investigated systems for rectification | 14 |

## 3 EXPERIMENTS AND CORRELATIONS

According to the mass transfer model the overall height of a transfer unit $HTU_{O,V}$ is not solely dependent on the physical properties of the system. It is also strongly influenced by the liquid-vapour ratio $\dot{L}/\dot{V}$, as shown by Eq.(3) and confirmed by experimental results; some of them are presented in Figs. 1 and 2. It is obvious that the height of a transfer unit $HTU_{O,V}$ is increasing with decreasing ratio of $\dot{L}/\dot{V}$. The highly pronounced reduction in $HTU_{O,V}$ at relatively low $\dot{L}/\dot{V}$-data occurs in the capacity range just above the loading point, which corresponds to the loads of approximately 70% of the flood load and which is normally taken as a basic for the column design.

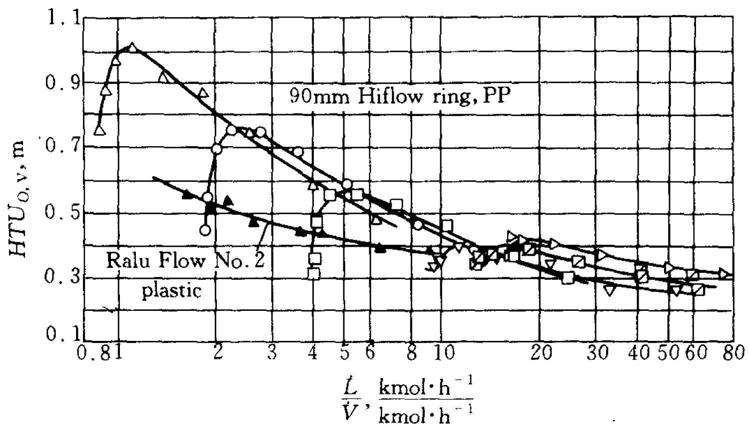


**Figure 1 Overall height $HTU_{O,V}$ of a transfer unit as function of the liquid-gas ratio $\dot{L}/\dot{V}$ for Ralu Flow rings and Hiflow rings at various liquid loads $u_L$**

(ammonia-air/water, 293K, $10^5$Pa)

$u_L$, $m^3 \cdot m^{-2} \cdot h^{-1}$: ▷ 120; ◪ 100; ▽ 80; □ 40; ○ 20; △ ▲ 10

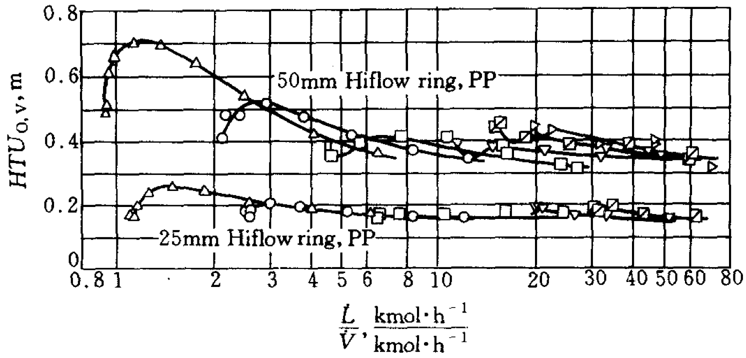


**Figure 2 Overall height $HTU_{O,V}$ of a transfer unit as function of the liquid-gas ratio $\dot{L}/\dot{V}$ for 25 and 50 mm plastic Hiflow rings at various liquid loads $u_L$**

(ammonia-air/water, 293K, $10^5$Pa)

$u_L$, $m^3 \cdot m^{-2} \cdot h^{-1}$: ▷120; ⊠ 100; ▿ 80; □40; ○ 20; △ 10

The values of $HTU_{O,V}$ valid for the loading point can now be read from Figs. 1 and 2 and plotted against the corresponding values of $\dot{L}/\dot{V}$, as shown in Figs.3 and 4. Thus, again, the $HTU_{O,V}$ values to be expected under loading conditions are continuously decreasing with increasing values of $\dot{L}/\dot{V}$.

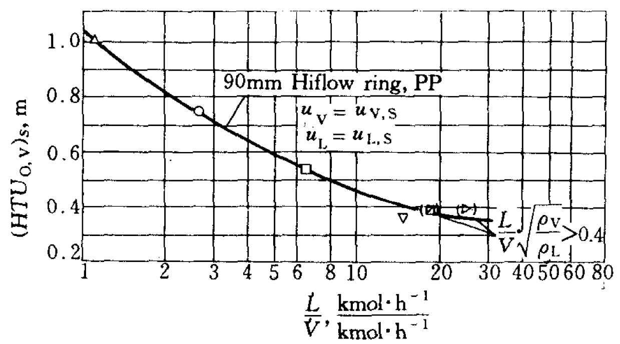


**Figure 3 Overall height $(HTU_{O,V})_S$ of a transfer unit at the loading point "S" as function of the liquid-gas ratio $\dot{L}/\dot{V}$ for 90 mm plastic Hiflow rings at various liquid loads $u_L$**

(ammonia-air/water, 293K, $10^5$Pa)

$u_L$, $m^3 \cdot m^{-2} \cdot h^{-1}$: ▷120; ⊠ 100; ▿ 80; □ 40; ○ 20; △ 10

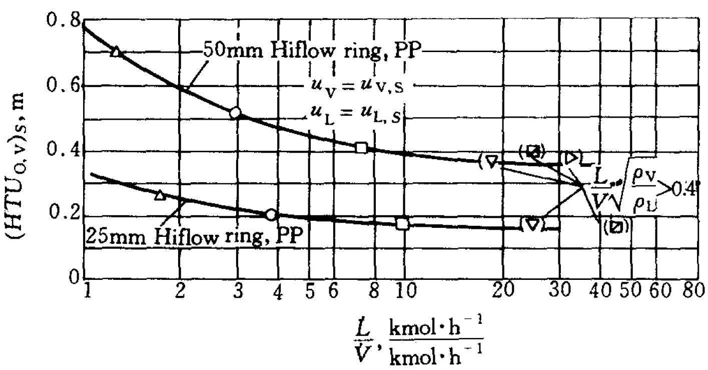


**Figure 4 Overall height $(HTU_{O,V})_S$ of a transfer unit at the loading point "S" as function of the liquid-gas ratio $\dot{L}/\dot{V}$ for 25 and 50mm plastic Hiflow rings at various liquid loads $u_L$**

(ammonia-air/water, 293K, $10^5$Pa)

$u_L$, $m^3 \cdot m^{-2} \cdot h^{-1}$: ▷ 120; ⊠ 100; ▿ 80; □ 40; ○ 20; △ 10

If the $HTU_{O,V}$ values for varying ratios of $\dot{L}/\dot{V}$ are now related to that valid for $\dot{L}/\dot{V}=1$, a plot of Fig.5 follows from Figs.3 and 4. It shows that all measured data obtained in the tests with three different packing sizes for the system ammonia-air/water are represented by only one and the same correlation line, as far as the capacity range below the phase inversion point is concerned. Measurements carried out in the range of capacities greater than the phase inversion load are indicated by brackets.

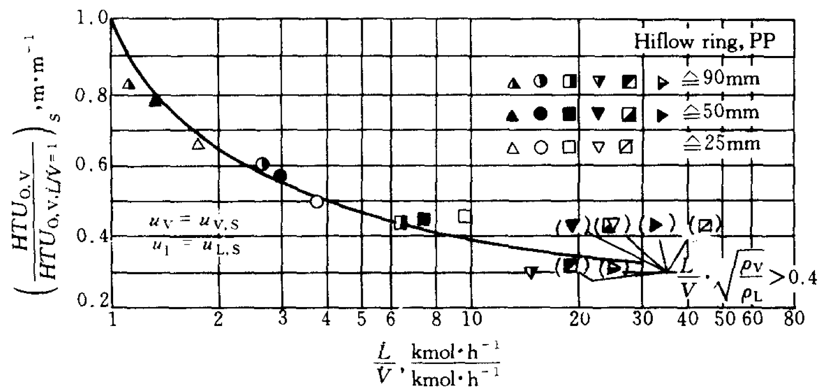


**Figure 5 Overall height of a transfer unit $HTU_{O,V}$ at the loading point "$S$" related to that valid for the liquid-gas ratio $\dot{L}/\dot{V}=1$ at the loading point "$S$" as function of $\dot{L}/\dot{V}$ for 25, 50 and 90mm plastic Hiflow rings** (ammonia-air/water, 293K, $10^5$Pa)

This dependency can also be obtained theoretically for other systems by evaluation of the model correlations, see Fig.6. It can be concluded from the diagram that mass transfer resistance is primarily present in the liquid phase at very low $\dot{L}/\dot{V}$ values and in the vapour or gas phase at very high values of $\dot{L}/\dot{V}$.

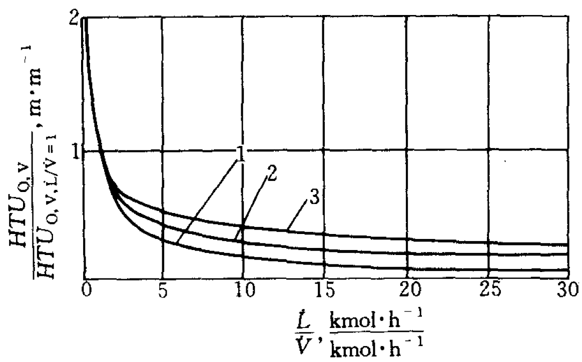


**Figure 6 Dependency in accordance with Fig. 5 theoretically obtained for various systems with plastic Ralu Flow rings No.2 and 50mm metal Hiflow rings**
1 – sulfur dioxide-air/water; 2 – ammonia-air/water; 3 – ethyl alcohol-air/water

The same function, but in a log-log scale, is presented in Fig.7. Thus, the influence of $\dot{L}/\dot{V}$ on mass transfer can be correlated by the simple function of Eq.(11), *i.e.*, there are relationships which depend on the system

$$\frac{HTU_{O,V}}{HTU_{O,V;\dot{L}/\dot{V}=1}} = \left(\frac{\dot{L}}{\dot{V}}\right)^n \tag{11}$$

Eq.(11) permits a good approximation for the ratio of the height of a gas side mass transfer unit for any $\dot{L}/\dot{V}$ ratio to the height corresponding to $\dot{L}/\dot{V}=1$ as a function of the liquid-vapour ratio $\dot{L}/\dot{V}$. As expected on the basis of the model equations and confirmed by their evaluation as shown in Fig.7, the average slopes of the lines in the diagram differ to an extent that depends on the system concerned. Thus, Eq.(11) allows a very easy estimation of $HTU_{O,V}$ values for any $\dot{L}/\dot{V}$, if $HTU_{O,V}$ values for $\dot{L}/\dot{V}=1$ are known either by experimental tests or by calculation methods.

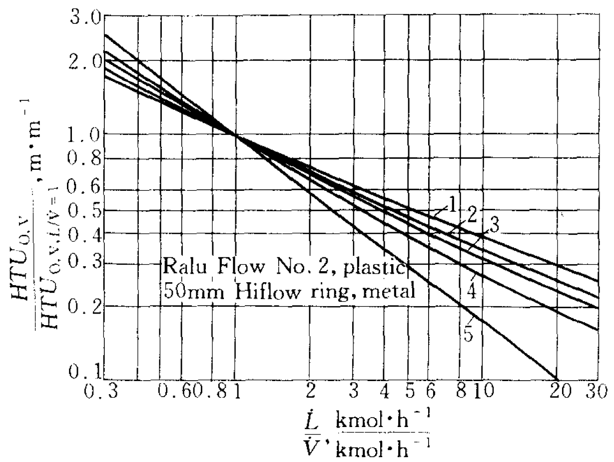


**Figure 7 Function according to Fig.6 in a log-ldog scale**
1—ethylalcohol-air/water; 2—chlorobenzene/ethylbenzene
3—ammonia-air/water; 4-acetone-air/water;
5—sulfur dioxid-air/water

It can also be concluded from the aforementioned considerations that the interrelationship of Eq.(12) exists, which allows the easy conversion of $HTU_{O,V}$ values from one phase ratio to another. For instance, the value of $HTU_{O,V}$ for any given $\dot{L}/\dot{V}=a$ can be calculated from the value of $HTU_{O,V}$ obtained by experiment at another liquid-vapour ratio of $\dot{L}/\dot{V}=b$

$$\frac{HTU_{O,V;\ \dot{L}/\dot{V}=a}}{HTU_{O,V;\ \dot{L}/\dot{V}=b}}=\left[\frac{(\dot{L}/\dot{V})_a}{(\dot{L}/\dot{V})_b}\right]^n \tag{12}$$

Further evaluation as illustrated in Fig.8 shows that the index $n$ depends on the resistance to mass transfer. The gas side resistance $R_{V,\ \dot{L}/\dot{V}=1}$, is expressed by Eq.(13) and the index $n$ can be described within a reasonable degree of accuracy as a linear function of $R_V$ according to Eq.(14)

$$R_{V;\ \dot{L}/\dot{V}=1}=\frac{HTU_{V;\dot{L}/\dot{V}=1}}{HTU_{O,V;\ \dot{L}/\dot{V}=1}} \tag{13}$$

$$n=0.\ 43R_{V,\ \dot{L}/\dot{V}=1}-0.75 \tag{14}$$

Fig.8 also indicates that the value of $n$ is smaller for systems with mass transfer resistance predominantly present in the gas or vapour phase than for those with mass transfer resistance predominantly present in the liquid phase. This is also confirmed by Fig.9.

These short-cut correlations are valid not only for operating conditions of the loading point($S$), but also for the phase ratios which differ by a factor $k<1$ from those $u_{L,S}/u_{L,S}$ valid for the loading capacity, see Eq.(15)

$$\frac{\dot{L}}{\dot{V}}=k\frac{u_{L,S}}{u_{V,S}}\frac{\rho_L}{\rho_V}\frac{\widetilde{M}_V}{\widetilde{M}_L} \tag{15}$$

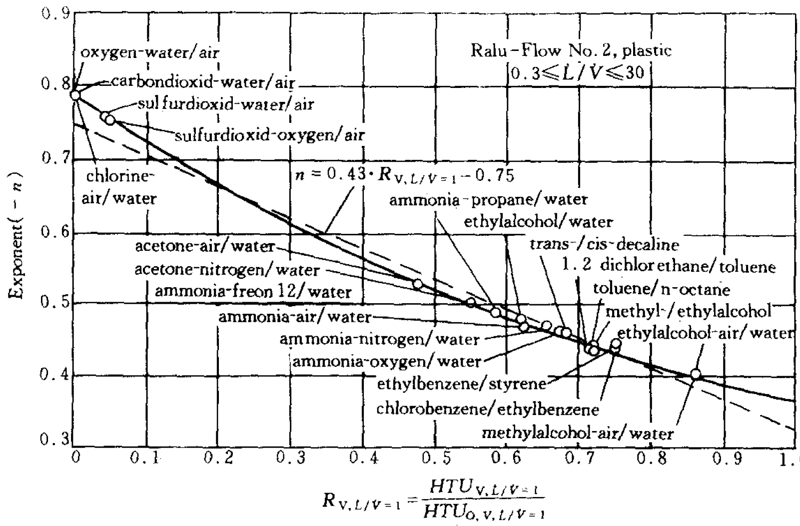


**Figure 8** Correlation of exponent $n$ in Eqs.(11) and (12) as function of mass transfer resistance $R_V$ for plastic Ralu-Flow No.2

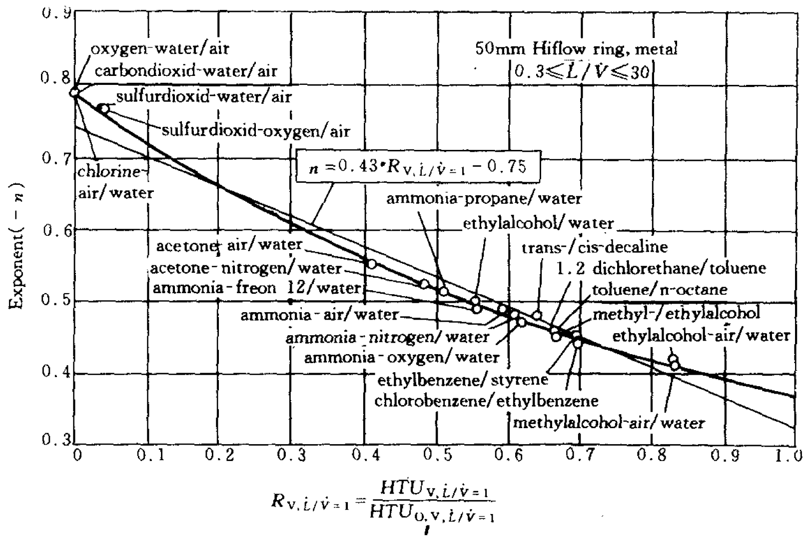


**Figure 9** Correlation of exponent $n$ in Eqs.(11) and (12) with mass transfer resistance $R_V$ for 50mm metallic Hiflow rings

However, there exists an upper limit of the validity range, which is characterised by the load conditions of the phase inversion point, when the liquid flow converts into a continuous phase and the gas consequently becomes a dispersed flow. The corresponding boundary flow parameter amounts to a value represented by Eq.(16)

$$\frac{L}{V}\sqrt{\frac{\rho_V}{\rho_L}} < 0.4 \tag{16}$$

The accuracy of the interrelationships is quite good. The mass transfer ratios obtained by Eqs.(11)−(14), differ from the set of the detailed model equations, Eqs.(3)−(7), by an average amount of 4.4%. It is only higher in case of extreme distributions of the resistance to mass transfer.

## 4 EXAMPLE

The acetone content of a spent air flowing at a rate of $11000\mathrm{m}^3 \cdot \mathrm{h}^{-1}$ at NPT has to be reduced from 1% (mol) of acetone to a final concentration of $100\ \mathrm{mg} \cdot \mathrm{m}^{-3}$ by absorption in $155\ \mathrm{m}^3 \cdot \mathrm{h}^{-1}$ water in a column packed with 50 mm plastic Ralu-Flow rings and operated at the loading point, corresponding to a column diameter of 1.5m. The overall height of a transfer unit $HTU_{\mathrm{O,V}}$ under process conditions has to be determined by employing a measured value $HTU_{\mathrm{O,V}}=1.44\mathrm{m}$, which was obtained in a pilot column at a gas velocity of $u_{\mathrm{V}}=3.1\ \mathrm{m} \cdot \mathrm{s}^{-1}$ and a liquid load of $u_{\mathrm{L}}=10\ \mathrm{m}^3 \cdot \mathrm{m}^{-2} \cdot \mathrm{h}^{-1}$.

**Solution:**

Required physical properties of the phases

$$M_{\mathrm{V}}=29\ \mathrm{kg} \cdot \mathrm{kmol}^{-1};\quad M_{\mathrm{L}}=18\ \mathrm{kg} \cdot \mathrm{kmol}^{-1}$$

$$\rho_{\mathrm{V}}=1.19\ \mathrm{kg} \cdot \mathrm{m}^{-3};\quad \rho_{\mathrm{L}}=1000\ \mathrm{kg} \cdot \mathrm{m}^{-3}$$

Phase loads of gas and liquid in the column to be designed

$$u_{\mathrm{V}}=\frac{V_{\mathrm{V}}}{A}=\frac{11000/3600}{(\pi/4)\ 1.5^2}=1.73\ \mathrm{m} \cdot \mathrm{s}^{-1}$$

$$u_{\mathrm{L}}=\frac{V_{\mathrm{L}}}{A}=\frac{155}{(\pi/4)\ 1.5^2}=87.7\ \mathrm{m}^3 \cdot \mathrm{m}^{-2} \cdot \mathrm{h}^{-1}$$

Phase ratio under design conditions

$$\left(\frac{\dot{L}}{\dot{V}}\right)_a=\frac{u_{\mathrm{L}}}{u_{\mathrm{V}}}\frac{\rho_{\mathrm{L}}}{\rho_{\mathrm{V}}}\frac{M_{\mathrm{V}}}{M_{\mathrm{L}}}=\frac{87.7/3600}{1.73}\frac{1000}{1.19}\frac{29}{18}=19.1$$

Phase ratio under pilot conditions

$$\left(\frac{\dot{L}}{\dot{V}}\right)_b=\frac{u_{\mathrm{L}}}{u_{\mathrm{V}}}\frac{\rho_{\mathrm{L}}}{\rho_{\mathrm{V}}}\frac{M_{\mathrm{V}}}{M_{\mathrm{L}}}=\frac{10/3600}{3.1}\frac{1000}{1.19}\frac{29}{18}=1.2$$

Exponent in Eq.(12) and resistance ratio for gas side mass transfer obtained from Fig.8

$$n=-0.53$$

$$R_{\mathrm{V},\dot{L}/\dot{V}=1}=0.475$$

Overall height of a gas side mass transfer unit obtained from Eq.(12)

$$(HTO_{\mathrm{O,V}})_a=(HTU_{\mathrm{O,V}})_b \cdot \left[\frac{(\dot{L}/\dot{V})_a}{(\dot{L}/\dot{V})_b}\right]^n=1.44\times\left(\frac{19.1}{1.2}\right)^{-0.53}=0.33\mathrm{m}$$

Exponent in Eq.(12) determined from Eq.(14)

$$n=0.43\times0.475-0.75=-0.535$$

and corresponding value of the overall height of a transfer unit

$$(HTU_{O,V})_a=(HTU_{O,V})_b\cdot\left[\frac{(\dot{L}/\dot{V})_a}{(\dot{L}/\dot{V})_b}\right]^n=1.44\times\left(\frac{19.1}{1.2}\right)^{-0.535}=0.33\text{m}$$

Applying the detailed theoretical model results in $HTU_{O,V}=0.34$m[6].

## 5 CONCLUSIONS

The method presented can be applied as a very simple approximation of the influence of the liquid-gas ratio on the effectiveness of mass transfer in packed columns, and efficiency values obtained at any liquid-gas ratio can be easily converted to those which are expected at other liquid-gas ratios.

## NOMENCLATURE

| | |
|---|---|
| $a$ | surface area per unit packed volume, $m^2\cdot m^{-3}$ |
| $a_{Ph}$ | interfacial area per unit packed volume, $m^2\cdot m^{-3}$ |
| $C$ | constant |
| $D$ | diffusion coefficient, $m^2\cdot s^{-1}$ |
| $d_h$ | hydraulic diameter, m |
| $d_s$ | column diameter, m |
| $F_V$ | vapour or gas capacity factor, $m^{-1/2}\cdot kg^{1/2}\cdot s^{-1}$ |
| $g$ | gravitational constant, $m\cdot s^{-2}$ |
| $H$ | height, m |
| $HTU$ | height of a mass transfer unit, m |
| $HTU_O$ | overall height of a mass transfer unit, m |
| $h_L$ | liquid holdup, $m^3\cdot m^{-3}$ |
| $k$ | coefficient |
| $L$ | mass flow of liquid, $kg\cdot h^{-1}$ |
| $\dot{L}$ | molar flow of liquid, $kmol\cdot h^{-1}$ |
| $M$ | molecular mass, $kg\cdot kmol^{-1}$ |
| $Ma_L$ | Marangoni number |
| $m_{yx}$ | slope of the equilibrium line, $kmol\cdot kmol^{-1}$ |
| $NTU_O$ | overall number of transfer units |
| $n$ | exponent |
| $R$ | magnitude for resistance to mass transfer |
| $u_L$ | superficial liquid load, $m^3\cdot m^{-2}\cdot h^{-1}$ |
| $u_V$ | superficial gas or vapour velocity, $m\cdot s^{-1}$ |
| $V$ | mass flow of gas or vapour, $kg\cdot h^{-1}$ |
| $\dot{V}$ | molar flow of gas or vapour, $kmol\cdot h^{-1}$ |
| $x$ | mole fraction in liquid phase, $kmol\cdot kmol^{-1}$ |
| $\Delta x$ | overall liquid concentration difference, $kmol\cdot mol^{-1}$ |
| $\beta$ | mass transfer coefficient, $m\cdot s^{-1}$ |
| $\varepsilon$ | void fraction, $m^3\cdot m^{-3}$ |
| $\eta$ | dynamic viscosity, $kg\cdot m^{-1}\cdot s^{-1}$ |
| $\lambda$ | stripping factor |
| $\nu$ | kinematic viscosity, $m^2\cdot s^{-1}$ |
| $\rho$ | density, $kg\cdot m^{-3}$ |
| $\sigma$ | surface tension, $kg\cdot s^{-2}$ |

### Subscripts

| | |
|---|---|
| $a$ | design condition |
| $b$ | pilot plant conditions |

| | |
|---|---|
| L | liquid |
| Ph | interfacial |
| *S* | loading point |
| V | vapour |

## REFERENCES


1 Billet, R., Festschrift der Fakultät für Maschinenbau, Ruhr-Universität Bochum, Bochum, 24 (1983).
2 Billet, R., *I. Chem. E. Symp. Ser.*, (104) A171 (1987).
3 Billet, R., *Chem. Eng. Technol.* **11,** 139 (1988).
4 Billet, P. and Schultes, M., *Chem. Eng. Technol.*, **16,** 1 (1993).
5 Schultes, M., Ph. D. Thesis, Ruhr-Universität Bochum, Bochum (1990).
6 Billet, R., Packed Towers, VCH Verlagsgeselllschaft, Weinheim (1995).