

A CORRELATION OF NTU PER UNIT COLUMN HEIGHT FOR RECTIFICATION OF BINARY MIXTURES

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A correlation is proposed in the paper of NTU per unit height of the column. The definition of NTU has been introduced in the preceding communication. The correlation has been tested by a set of experimental data obtained by rectification of various binary mixtures at total reflux on a vertical expanded metal sheet packing.

A modified definition of the number of transfer units (NTU) has been introduced in the previous communication¹ and the new definition proved suitable for expressing the effectiveness of rectification columns.

In this paper a correlation of the number of the modified transfer units per column height is introduced and it is tested on an extensive set of experimental data obtained during rectification of binary mixtures under various experimental conditions and a total reflux. The packing used in the column was made of vertical strips of expanded metal sheet.

THEORETICAL

The mean overall mass transfer coefficient is defined by

$$\bar{K} = N_{0G} G/A \quad (1)$$

where

$$N_{0G} = \int_{y_1}^{y_2} \frac{dy}{y^* - y + x - x^*} \quad (2)$$

Eq. (1) may be written alternatively as

$$\bar{K} = n_G u_b / (av), \quad (3)$$

The mass transfer coefficient according the previous paper¹ may be expressed also as

$$\bar{K} = \frac{1}{A} \int_A \frac{K_g K_1}{K_g + K_1} dA \quad (4)$$

Because

$$\frac{K_g}{K_1} = \frac{x - x^*}{y^* - y} = \frac{1}{m} \quad (5)$$

we may write Eq. (4) also in the form

$$\bar{K} = \frac{1}{A} \int_A \frac{m}{1 + m} K_g dA \quad (6)$$

Similarly

$$\bar{K}_g = \frac{1}{A} \int_A K_g dA \quad (7)$$

and hence

$$\bar{K} = \bar{K}_g \int_A \frac{m}{1 + m} K_g dA \bigg/ \int_A K_g dA \approx k \bar{K}_g. \quad (8)$$

The coefficient of mass transfer, \bar{K} , is thus proportional to the overall coefficient of mass transfer, \bar{K}_g , relating to the driving force in the vapour phase.

Based on an analysis of hydrodynamic conditions in the proximity of the interface the following relationship has been derived for the coefficient of mass transfer under the turbulent motion of fluids²

$$K_G = [DF(v/D)] / [\lambda_p + \delta_1 F(v/D) + \lambda_t \Phi(v/D)] \quad (9)$$

where

$$K_G = Gv dy / [(y^* - y) dA] \quad (10)$$

$$F(v/D) = 1 + (1/3)(v/D) \quad \text{for } (v/D) \leq 1, \quad (11a)$$

$$F(v/D) = (2/\sqrt{\pi})(v/D)^{0.5} \quad \text{for } (v/D) \geq 3, \quad (11b)$$

$$F(v/D) = 1.32(v/D)^{0.358} \quad \text{for } 1 \leq (v/D) \leq 3, \quad (11c)$$

$$\Phi(v/D) = 2F(v/D) / [(v/D) f(v/D)] - 1 \quad (12)$$

and

$$f(v/D) = 1 + (8/\pi^2) \sum_{n=0}^{\infty} [1/(2n+1)^2] \exp[-(2n+1)^2 \pi^2 / (v/D)]. \quad (13)$$

In our case, when we deal with a mixture of vapours exhibiting relatively low value of the Schmidt number ($0.45 \leq Sc \leq 1.67$) and the turbulent flow of the vapour in a duct with rough walls (expanded metal sheet) we may neglect the effect of the laminar boundary layer ($\delta_1 = 0$).

For λ_p we shall take the relation²

$$u^* \lambda_p / \nu = 20 \quad (14)$$

and for λ_t the relation²

$$\lambda_t = d_e / [2f) u_b d_e / \nu]^3]^{1/4} . \quad (15)$$

From Eqs (3), (8), (10) and definition of K_G follows

$$\bar{K}_G = n_G u_b / a_f \quad (16)$$

in terms of the fictitious interfacial area per unit volume of the column ($a_f = ka$). After substituting from Eqs (3), (14), (15) and (16) into Eq. (9) and after some arrangement we obtain

$$\begin{aligned} (a_f/a_0) = [20 + 0.707\Phi(v/D) (u_b d_e / \nu)^{1/4} \cdot (f/2)^{1/4}] / \\ / [F(v/D) (a_0/n_G) (f/2)^{1/2} / (v/D)] . \end{aligned} \quad (17)$$

The introduction of the ratio of the true interfacial surface area to the area of the dry packing per unit volume permits us to some extent to judge the degree of utilization of the surface area of the packing and eventually its changes.

EXPERIMENTAL

Experimental data processed according to Eq. (17) were obtained by rectification of binary mixtures under total reflux in a 50 mm in diameter column packed with vertical sheets of expanded metal. The size of mesh of the expanded metal was 10×5 mm, the effective length of individual strips of the metal was 1600 and 1800 mm. The spacing of the sheets was 4.5 mm. Thus $a_0 = 183$ l/m.

Nine various binary mixtures were used of which seven were rectified under atmospheric pressure and the remaining two at vacuum.

Table I shows the ranges of principal parameters appearing in Eq. (17) for individual binary mixtures.

The diffusivities were computed using Hirschfelder's relation and the dynamic viscosities from Bromley-Wilke's³ equation.

The calculation of the relation a_f/a_0 was carried out on a computer. Because the specific interfacial area and hence also the fictitious interfacial area should depend primarily on the density of irrigation, L , the values of the ratio a_f/a_0 were plotted in Fig. 1a,b as functions of this parameter. Fig. 1a shows all experimental points for vacuum rectification. For clarity, Fig. 1b shows only the courses of the dependence for individual systems.

TABLE I

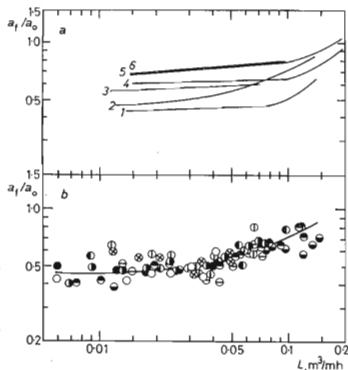
System	Operating pressure Torr	Sc	Re	$f/2 \cdot 10^{+2}$
Methanol-water		0.527-0.567	349.0-3 650	5.51-2.82
Ethanol-water		0.452-0.706	153.9-2 889	12.53-2.92
Benzene-n-heptane		1.300-1.578	792.5-9 247	4.03-2.18
Tetrachlormethane-benzene	760	0.900-0.920	574.5-5 324	4.37-2.50
n-Heptane-toluene		1.350-1.670	575.0-7 369	4.37-2.31
Cyclohexane-n-heptane		1.037-1.128	411.7-7 063	4.75-2.33
Benzene-toluene		1.470-1.500	575.0-6 678	4.34-2.36
Ethylbenzene-styrene	50	0.731-0.951	610.0-2 585	4.30-3.10
	100	0.830-0.876	517.0-3 164	4.18-2.85
	150	0.770-0.784	608.0-3 405	4.16-2.80
Chlorobenzene-ethylbenzene	25	0.774-0.806	365.0-2 545	5.27-3.01
	50	0.699-0.716	341.0-3 467	5.64-2.79
	100	0.726-0.741	467.5-3 979	4.58-2.69
	200	0.720-0.737	452.4-4 649	4.64-2.59
	400	0.710	451.9-5 510	4.64-2.48
	760	0.701-0.727	484.6-6 039	4.56-2.47

FIG. 1

Plot of a_f/a_0 versus Density of Irrigation for a) All Experimental Systems and b) for Vacuum Rectification

a 1 Methanol-water; 2 vacuum rectification (chlorobenzene-ethylbenzene, ethylbenzene-styrene); 3 ethanol-water; 4 benzene-toluene, benzene-n-heptane, cyclohexane-n-heptane; 5 n-heptane-toluene; 6 tetrachloromethane-benzene.

b Chlorobenzene-ethylbenzene, Torr: ○ 25; ● 50; ⊙ 100; ⊕ 200; ⊗ 400; ⊖ 760. Ethylbenzene-styrene, Torr: ⊗ 50; ⊙ 100; ⊕ 150.



DISCUSSION

From Table I it can be seen that the experiments cover systems of markedly different physical properties and wide ranges of operating conditions. It may thus be expected that the specific interfacial area either true or fictitious will depend not only on the density of wetting but also on some physical properties of the mixtures such as *e.g.* the surface tension or the contact angle between the liquid and the packing. A quantitative assessment of this effect is very difficult as both temperature and composition controlling the physical properties vary along the column.

From Fig. 2 it is apparent that the plots of a_t/a_0 versus density of wetting have an analogous course except that they appear mutually shifted for individual systems. This may be caused either by different value of k or contact angle or the inaccuracy of the determination of the diffusion coefficient and the dynamic viscosity from the theoretical relationships. The mean error of Hirschfelder's relation is set at 6% while for the Bromley-Wilke's relation the estimated error amounts to about 4.9%.

Examining the courses of these dependences we conclude that these comport with what may be expected from visual observation.

Increasing density of wetting causes the hold-up and the specific interfacial area to slowly grow. But not until we approach the flooding does the hold-up significantly grow, the growth being accompanied eventually by froth formation and a marked increase of specific interfacial area.

In fact, it can be inferred that the value (a_t/a_0) corresponds to the expected value (a/a_0) . The extent to which this qualitative assessment agrees with reality could be ascertained only from measurements of interfacial area.

In the framework of this paper the parameter (a_t/a_0) should be looked upon as one whose value must be known in order that we be able to evaluate n_G from Eq. (17) for given conditions.

LIST OF SYMBOLS

A	interfacial area (m^2)
a	specific interfacial area (l/m)
a_t	fictitious specific interfacial area (l/m)
a_0	specific surface of packing (l/m)
D	diffusion coefficient (m^2/s)
d	spacing of strips of sheets of packing (m)
d_e	equivalent diameter ($d_e = 2d$) (m)
$F(v/D)$	function defined by Eqs (11a,b,c)
f	friction coefficient
$f(v/D)$	function defined by Eq. (13)
G	molar flow rate of vapours (Kmol/s)
k	constant in Eq (8)

\bar{K}	overall coefficient of mass transfer defined in Eq. (4) (Kmol/m ² s)
K_G	coefficient of mass transfer defined in Eq. (10) (m/s)
K_g	overall coefficient of mass transfer related to vapour phase (Kmol/m ² s)
K_l	overall coefficient of mass transfer related to liquid phase (Kmol/m ² s)
L	density of irrigation (m ³ /m hours)
m	defined by Eq. (5)
N_{0G}	total number of modified transfer units
n_G	number of transfer units per unit column height (1/m)
u	velocity (m/s)
u_b	superficial velocity (m/s)
u^*	friction velocity ($u^* = u_b \sqrt{f/2}$) (m/s)
v	molar volume of vapour mixture (m ³ /Kmol)
y	mole fraction of low boiling component in vapour
x	mole fraction of low boiling component in liquid
δ_1	thickness of laminar layer (m)
λ_p	thickness of transition layer (m)
λ_l	local degree of turbulence (m)
ν	kinematic viscosity (m ² /s)

Indices

*	at equilibrium
—	mean value

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