Korean J. of Chem. Eng., 12(3), 313-319 (1995)

A STUDY ON CHARACTERISTICS OF A MODERN STRUCTURED PACKING

Sung Yong Cho†, Youn Yong Lee and Seung Jai Kim*

CFC Center, KIST
*Chonnam National University
(Received 7 October 1994 • accepted 19 March 1995)

Abstract—The hydraulic characteristics including dry pressure drops, liquid holdups, flooding data, effective interfacial areas, and wet pressure drops of a modern structured packing (Sulzer BX) were studied using the air-water system. As a result, a predictive equation for the wet pressure drops of this structured packing at below the flooding point was derived for the design of the distillation column. The equation was tested with the experimental data obtained from the practical vacuum distillations. It was suggested that the equation is useful for the vacuum distillation under the flooding point, but the deviation is increased above the flooding point.

Key words: *Structured Packing, Pressure Drops, Flooding Data*

INTRODUCTION

During the last few years, the packed columns have been widely adopted to the process of chemical and allied industries. The packed columns have been mainly used for the mass transfer process as well as the direct heat transfer between two phases. Even though the use of the packed columns in the chemical processing industry dates back many decades, the applications of the packed columns were limited to the corrosive systems or to the columns of relatively small diameters and these columns were rather crudely designed. However, nowadays the use of packings in large commercial distillation columns is serious considered, in accordance with the development of through-flow packings and high efficient structured packings.

The advantages of structured packing are the elimination of the drags associated with the conventional dumped packings, the allowance of the low pressure drop per theoretical stage at high load without sacrificing efficiency or capacity, and the restriction for the thermal decomposition [Fair and Bravo, 1990; Bravo et al., 1986; Billet and Mackowiak, 1988]. Furthermore, the structured packings have higher effective interfacial areas than those of conventional random packings. These advantages allow a favorable and wide application. It is generally conceded today that, for many distillations at either vacuum or moderate pressure, the structured packing can be more effective than trays and other types of packings [Fair and Bravo, 1990].

In packed column design, one of the important variables is the hydraulic characteristics in the tower. Furthermore, in vacuum distillation, low pressure drop is necessary for the successful operation and an accurate prediction for the pressure drop is essential for the optimum design.

This article focuses to the experimental study on hydraulic characteristics of a modern structured gauze-type packing (Sulzer BX) and the suggestion of a predictive equation for the wet pressure drop.

†To whom all correspondences should be addressed.

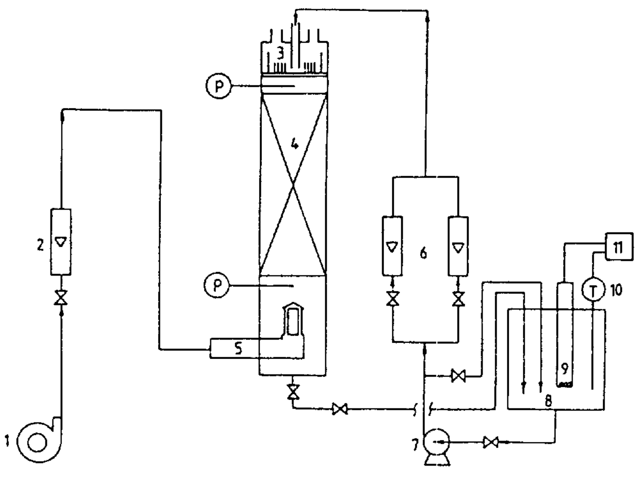


Fig. 1. Schematic diagram of apparatus used in air-water system.

1. Air blower	7. Liquid pump
2. Air rotameter	8. Reservoir
3. Liquid distributor	9. Heater
4. Packed column	10. Thermometer
5. Gas distributor	11. Temperature controller
6. Liquid rotameter	P. Differential manometer

EXPERIMENT

Figs. 1 and 2 show a schematic diagram of the apparatus employed and the details of a packed column used in this work, respectively. The column (I.D. = 15 cm) was made from polymethyl metacrylate tube and packed to a depth of 185 cm with structured packings (Sulzer BX). The shapes and dimensions of the structured packing are shown in Fig. 3 and Table 1, respectively. Air flow, provided by a blower, to the bottom of the column was metered by a calibrated set of rotameter and distributed by the gas distributor.

Both inlet and outlet gas temperatures were measured at just below and above the column by a thermometer with the iron-constantan thermocouple. The air passed upward through the packing

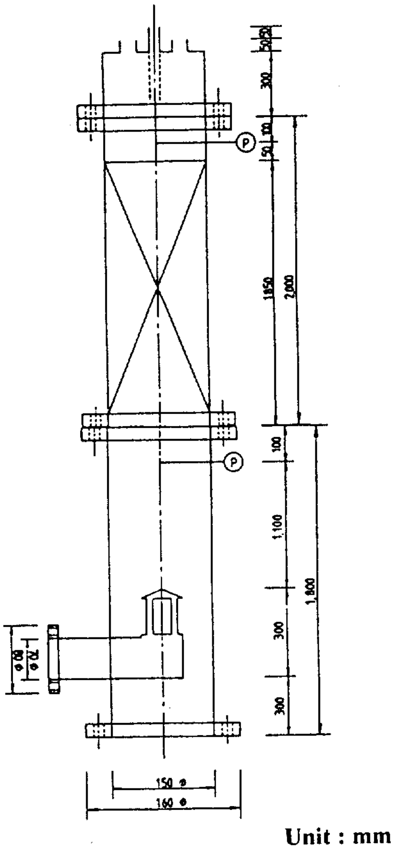


Fig. 2. Details of packed column.

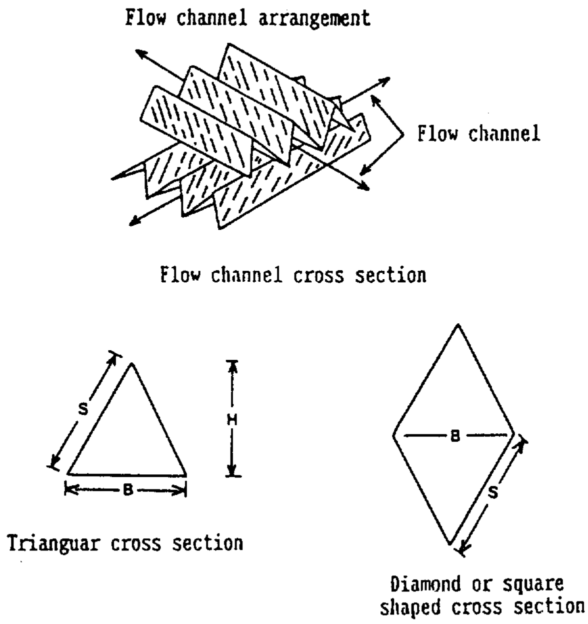


Fig. 3. Flow channel geometry.

and vented to the atmosphere. Then dry pressure drops caused by the frictional resistance of gas flow were measured by the inclined manometer (Dwyer Instruments Inc.).

Water, which was metered by rotameter, was supplied to the liquid distributor through the top of the column by using the

Table 1. Dimensions of structured packing used in air-water system

Material	stainless steel (316L)
Diameter	0.15 m
Height	0.185 m
Weight	0.643 Kg
Surface area	500 m^2/m^3
Equivalent diameter*	0.00645 m
Void fraction	0.9
Height of triangle (H)	0.006 m
Base of triangle (B)	0.012 m
Corrugation spacing (S)	0.009 m
Angle of inclination of flow channel from the horizontal (θ)	55°

*For the triangular and square-shaped cross section in Fig. 3, an arithmetic average of those two hydraulic radii is taken [2]. The resulting equivalent diameter is $d_{eq}=B\cdot H[1/(B+2S)+1/2S)]$.

magnetic pump from the reservoir at constant temperature. The water passed downward through the packing and returned to the reservoir located at the bottom of the column.

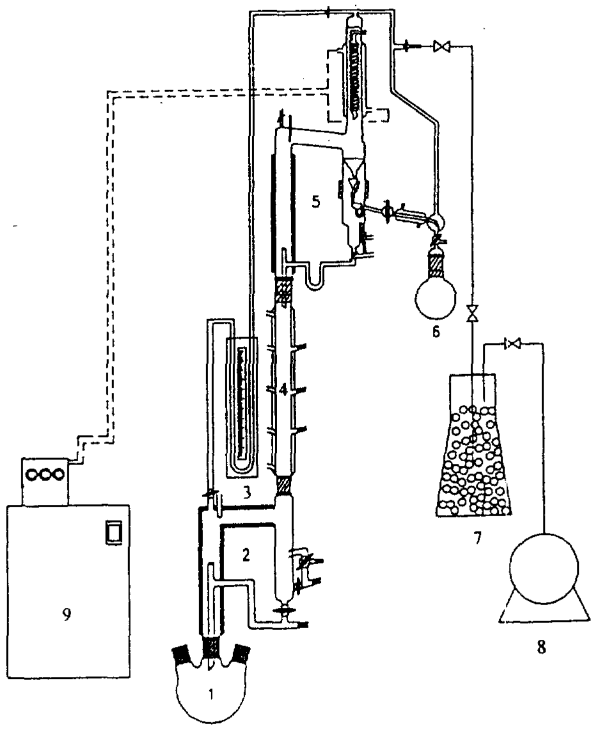
At the first stage, water-flow was maintained for approximately 1/2 hr, in order to wet the packing thoroughly, then the desired flow rate was set. When the packing was irrigated with a constant liquid flow rate and the steady-state operation was sets, the total pressure drops and dynamic holdups were measured. The total pressure drops were measured by the inclined manometer installed between below and above the packing. In order to measure the dynamic holdups, liquid level had been noted in a tank at the bottom of the column, then followed by the simultaneous shutdown of the liquid inlet and outlet valves. After about 30 minutes later, the holdups trickled into the collecting vessel and the liquid level should be lowered to the mark by opening a valve. The volume thus runs off was then measured and can be regarded as the dynamic holdups. In order to avoid errors in the measurement, the volume of liquid that trickled onto the bed through the distributor was measured and calibrated.

The effective interfacial areas in this column were measured from CO_2 absorption experiments in K_2CO_3-$KHCO_3$ buffer solution. To measure the effective interfacial areas in this packed column, air was used for the gas phase and CO_2 contained in air was removed by passing the column. The liquid phase was K_2CO_3-$KHCO_3$ buffer solution and was kept at 21± 1℃ in the constant temperature reservoir. The liquid was drawn up with a pump upto the top of the column to contact the gas rising from the bottom of the column. The mentioned procedures were repeatedly carried out at various liquids and gases flow rates.

To test the correlation from the air-water system, a practical vacuum distillation system was designed as shown in Fig. 4. The structured packings of the practical vacuum distillation column have the same material and geometry as the packings in the air-water system. The material and dimensions of this packing are listed in Table 2.

RESULTS AND DISCUSSION

Figs. 5 and 6 are logarithmic plots of experimental data obtained in this work on about pressure drops and fractional liquid holdups, respectively. In Fig. 5, the dry pressure drop with no liquid flow is almost straight against the F_s-factor $(=U_{gs}\cdot\rho_g^{1/2})$ of gas. On the other hand, wet pressure drops appear to start in parallel to the



1. Reboiler
2. Bottom head
3. Manometer
4. Structured packed column
5. Reflux head and condenser
6. Reservoir
7. Filter
8. Vacuum pump
9. Constant temperature circulator

Fig. 4. Schematic diagram of apparatus used in vacuum distillation system.
(system fluid: phenol/ortho-secondary butyl phenol)

Table 2. Dimensions of structured packing used in vacuum distillation system

Material	stainless steel (316L)
Diameter	0.025 m
Height	0.057 m
Weight	0.006 Kg
Surface area	500 m^2/m^3
Equivalent diameter*	0.0019 m
Void fraction	0.9
Height of triangle (H)	0.002 m
Base of triangle (B)	0.005 m
Corrugation spacing (S)	0.002 m
Angle of inclination of flow channel from the horizontal (θ)	53°

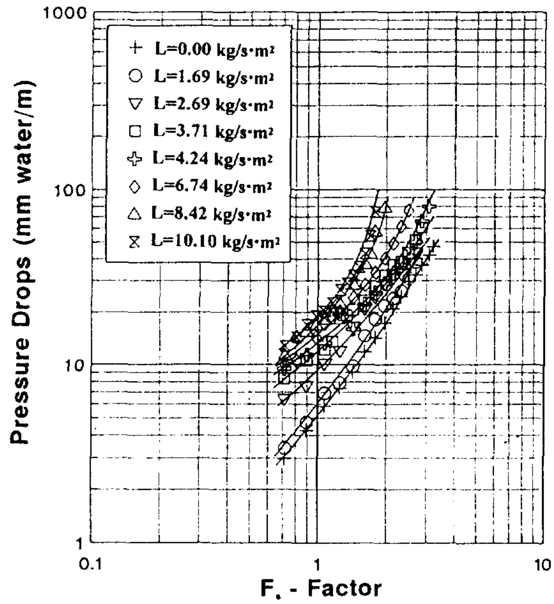


Fig. 5. Pressure drops against F_s-factors.

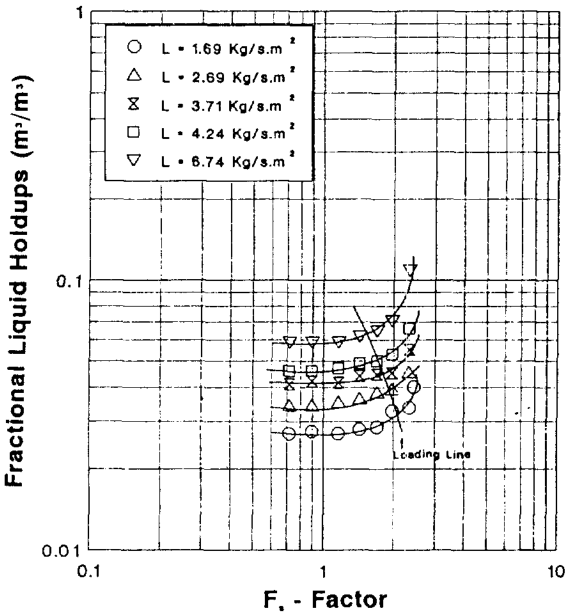


Fig. 6. Fractional liquid holdups against F_s-factors.

dry pressure drops at low liquid flow rate. However, its slopes gradually increase as the gas and liquid flow rates increase.

In Fig. 6, fractional liquid holdup curves are found to be coincided with the course described by other workers [Billet and Mackowiak, 1988; Billet, 1988]. They were almost constant at the preloading region and began to rise just before the estimated loading point. Below the loading point, the liquid holdups were independent on gas flow rates, and increased with increasing the liquid flow rate.

Flooding data in air-water systems for Sulzer BX and other structured packings [Fair and Bravo, 1990] are shown in Fig. 7. This plot based on hydraulic flood represents the orderly change of flooding velocity with changes in the liquid/gas ratio. It also shows that the capacity limit decreases with increasing the specific surface area of packings [Fair and Bravo, 1990].

1. Dry Pressure Drops

In single phase gas flow in the packed column, where there is no liquid wetting the packing surface, the dry pressure drop can be described by the general Fanning's friction law. The dry pressure drop depends on the effective gas velocity, the hydraulic diameter and the friction factor that depend on the geometry of packing and on the Reynolds number [Ergun, 1952; Mersmann and Deixer, 1986].

Therefore, dry pressure drops in the packed column can be

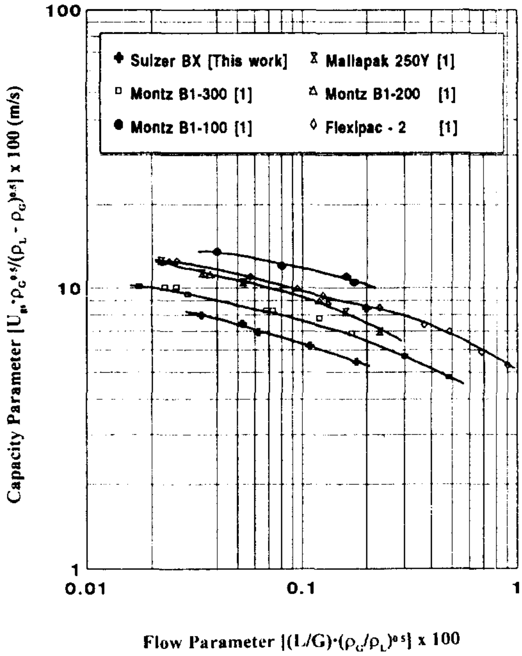


Fig. 7. Flooding data for structured packings.

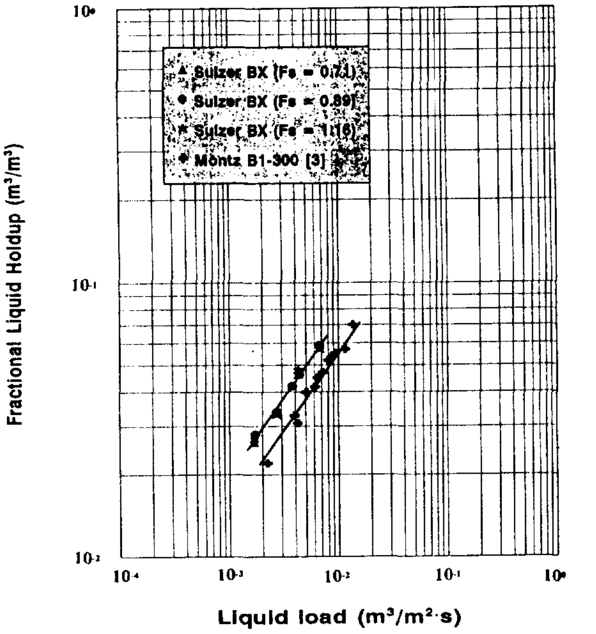


Fig. 9. Fractional liquid holdups of structured gauze packings against liquid loads.

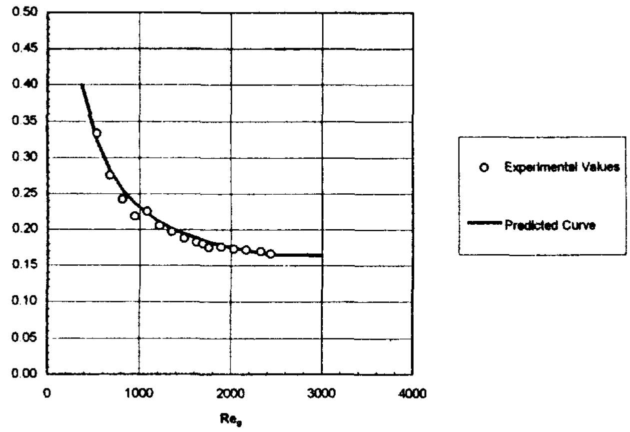


Fig. 8. Friction factor against the Reynolds number in dry column.

expressed by Eq. (1), and then friction factors are expressed by Eq. (2).

$$P_d = (f \cdot \rho_g \cdot U_{ge}^2)/(d_{eq} \cdot g_c) \quad (1)$$

$$f = C_1 + C_2/Re_g \quad \text{for } 1.0 < Re_g < 10^4 \quad (2)$$

where $Re_g = (d_{eq} \cdot U_{ge} \cdot \rho_g)/\mu_g$.

The values of constants C_1 and C_2 in Eq. (2) can be determined by experimental data for the dry pressure drops. The best value was determined by the regression of f vs. $1/Re_g$ and these led to the following equation:

$$f = (0.12 + 110/Re_g) \quad (3)$$

The prediction curve and experimental values are shown in Fig. 7 and this curve agrees with experimental data within 5% error. Therefore, a predictive equation for dry pressure drops of this structured packing can be expressed by Eq. (4) which is derived by combining Eq. (1) and Eq. (3).

$$P_w = [C_1 + C_2/Re_g][F_s^2/(\varepsilon^2 \cdot \sin^2\theta \cdot d_{eq} \cdot g_c)] \quad (4)$$

2. Liquid Holdups

In the case of an irrigated packing, the total liquid holdup, h_t, consists of two contributions; the static liquid holdup, h_{sta} that remains in the void and cavities of the packing, and the dynamic liquid holdup, h_{dyn} [Mersmann and Deixer, 1986]:

$$h_t = h_{sta} + h_{dyn} \quad (5)$$

The static holdup is influenced by the flowing liquid and this contribution decreases with increasing dimensionless liquid load [$=(Fr_L^2/Re_L)^{1/3}$] [Mersmann and Deixer, 1986]. According to the results of Blass and Kurtz and Mersmann, when the values of dimensionless liquid load are higher than 2×10^{-3}, the total hold-up nearly equals to the dynamic holdup.

Above a certain irrigation rate, Bemer [Bemer and Kalise, 1978] and Billet [Billet, 1988] reported that Eq. (6) was satisfactory below the loading point, where liquid holdup is not influenced by the gas velocity:

$$h_t \cong h_{dyn} = A \cdot Fr^n \quad (6)$$

Under the assumption that the total holdup is nearly equal to dynamic holdup at turbulent region, the relationships of the fractional liquid holdups and liquid velocities in Fig. 9 give an exponent (=n) in Eq. (6). Therefore, the expression for the total liquid holdups is as follows:

$$h_t = A \cdot Fr^{1/3} \quad (7)$$

3. Effective Interfacial Areas

In the absorption system accompanied by a pseudo first-order reaction, its governing equation may be expressed as the following [Danckwerts, 1962]:

$$\frac{\partial C}{\partial \theta} = D\frac{\partial^2 C}{\partial X^2} - K_1 \cdot C \quad (8)$$

Its boundary conditions are

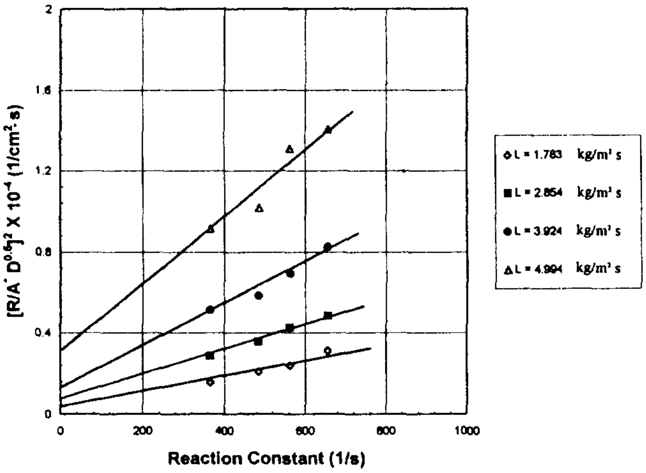


Fig. 10. Danckwerts' plot at four liquid flow rates.

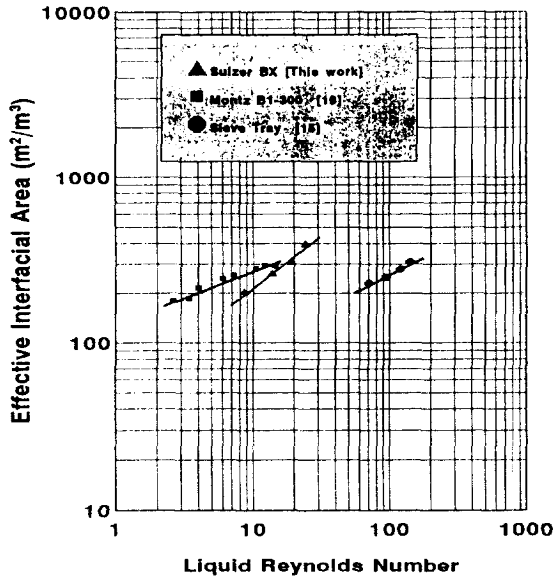


Fig. 11. Effective interfacial areas vs. liquid flow rates.

$$C=0 \text{ at } X>0,\ \theta=0$$
$$C=C^* \text{ at } X=0,\ \theta>0$$
$$C=0 \text{ at } X>\infty,\ \theta=0 \tag{9}$$

Through the Laplace transform, its solution can be obtained as

$$C=C^*\cdot\exp[(-X/D)\cdot(D\cdot K_1+K_L^2)^{0.5}] \tag{10}$$

Robert and Danckwerts [Danckwerts, 1962] proposed the surface renewal model, assuming that the liquid element at the surface is displaced with fresh liquid element in bulk and has an age distribution from zero to infinite.

In Danckwerts' model, the average absorption rate per unit area is

$$R=C^*\cdot(K_L^2+D\cdot K_1)^{0.5} \tag{11}$$

This equation may be rearranged in following form:

$$(R\cdot a/C^*\cdot D^{0.5})^2=a^2\cdot K_1+(K_L\cdot a)^2/D \tag{12}$$

When NaOCl is used as the catalyst, K_1 is equal to $K_{H_2O}+K_{OCl^-}$

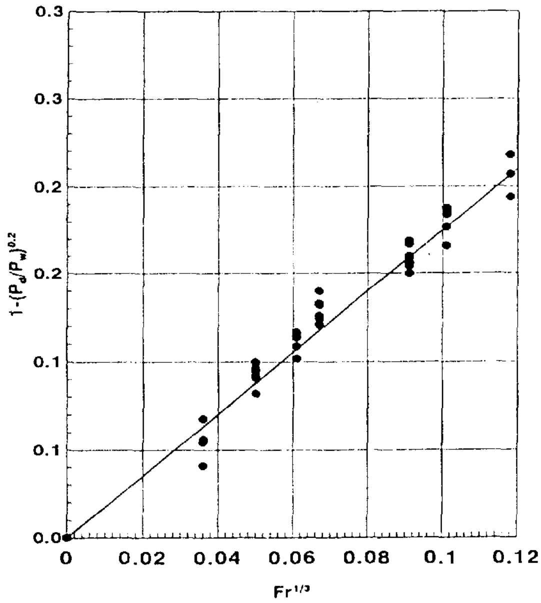


Fig. 12. Plot for determination of constant C_3 in Eq. (15).

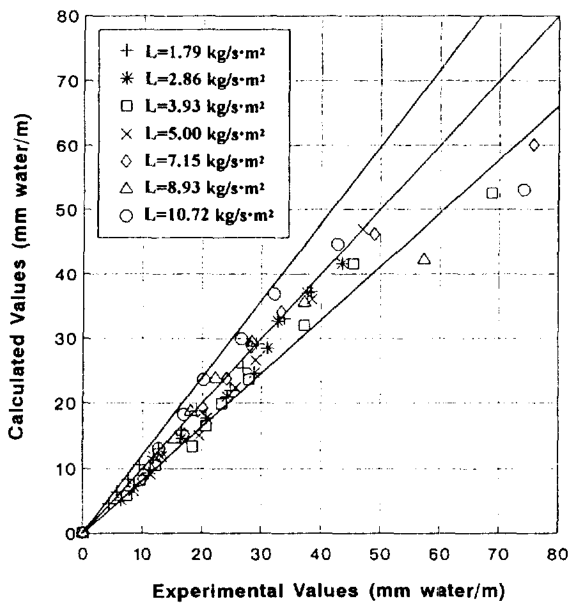


Fig. 13. Comparison of calculated values with experimental values for wet pressure drop in air-water system.

$[OCl^-]$.

Pohorecki [Pohorecki, 1976] suggested that the dependence of K_{OCl^-} on the composition of solution at 21℃ may be expressed by following equation.

$$K_{OCl^-}=1518+1318[CO_3^{--}]/[HCO_3^-] \tag{13}$$

Fig. 10 shows Danckwerts' plot for this packing at four liquid flow rates, when F_s-factor of gas is 0.9. From the slopes of lines in Fig. 10, the effective interfacial areas of this packing were determined.

Fig. 11 shows that the effective interfacial areas in structured packing column increase with the liquid flow rates and are higher than those in sieve plate column that is based on the liquid volume on a sieve plate [Cho et al., 1990].

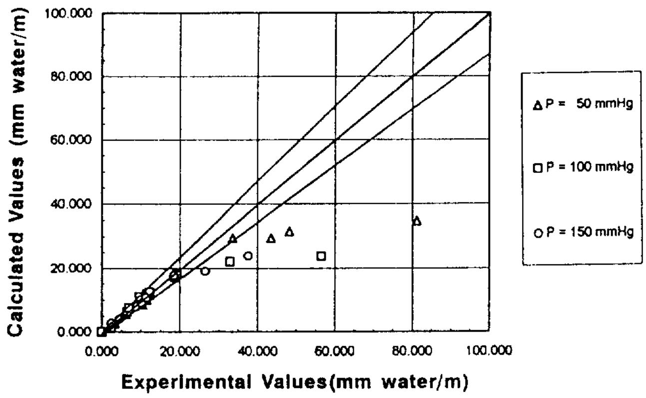


Fig. 14. The model test (1) in phenol/ortho-sec butyl phenol system.
(column diameter=0.025 m, column height=1.14 m, L/V=1)

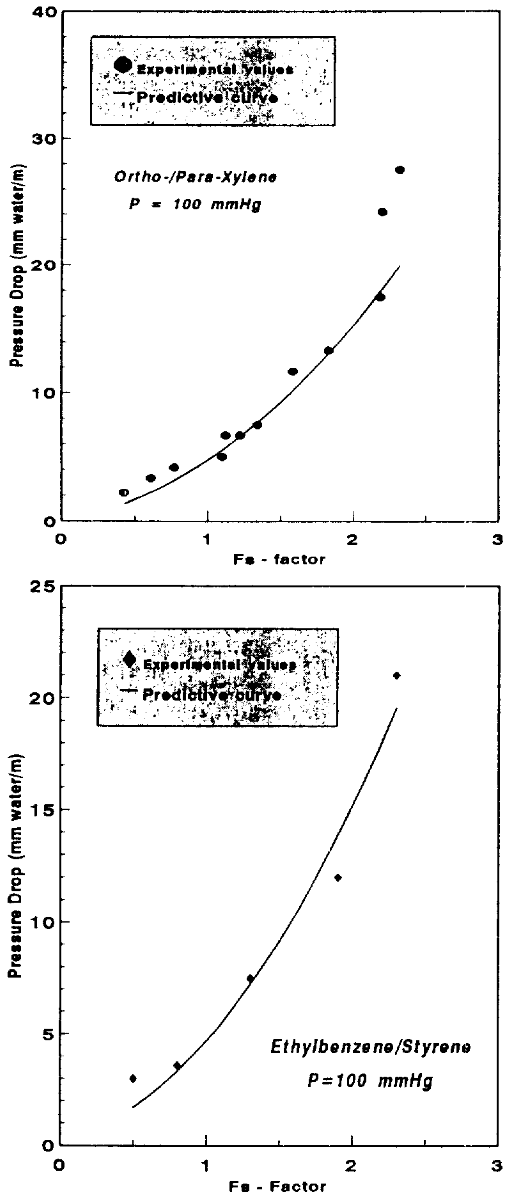


Fig. 15. The model test (2) in o-/p-xylene and ethylbenzene/stylene system.
(column diameter=0.25−1 m, L/V=1) [Billet and Mackowiak, 1988].

4. Wet Pressure Drops in Irrigated Packing

When a packing is irrigated, the space available for vapor to pass through the column is reduced due to liquid holdup. Therefore, the wet pressure drops increase with increasing the liquid holdups and are correlated by Eq. (14) [Billet, 1988; Buchanan, 1969]:

$$P_w/P_d=[1/(1-K\cdot h_t)]^5 \quad (14)$$

Combining Eqs. (7) and (14), a final correlating equation for the wet pressure drop of a structured packing can be expressed as follows.

$$P_w/P_d=[1/(1-C_3\cdot Fr^a)]^5 \quad (15)$$

where $C_3=A\cdot K$

Fig. 12 shows how the constant, C_3 in Eq. (15) was determined. From the slope of the line in Fig. 12, the value of C_3 for Sulzer BX packing used in this work was estimated. Therefore, a predictive equation for wet pressure drops of the Sulzer BX packing is suggested by Eq. (16).

$$P_w=[C_1+C_2/Re_g][F_s^2/(\varepsilon^2\cdot\sin^2\theta\cdot d_{eq}\cdot g_c)][1-C_3\cdot Fr^a]^{-5} \quad (16)$$

where $C_1=0.12$, $C_2=110$, $C_3=1.7$, $a=1/3$.

Fig. 13 shows the comparative plot of the experimental data with the calculated values of wet pressure drops in air-water system. The agreement between calculated and experimental values below loading points were within error 10% in this Figure. But the deviation was getting larger over the loading point, because that liquid holdup sharply increases over the loading point.

5. Test the Predictive Equation

Figs. 14 and 15 are the comparative plots of the predictive curve by the equation with the experimental data obtained from the practical vacuum distillation conditions. These figures show that the predictive equation for the wet pressure drops of the structured packing (Sulzer BX) can apply to distillation systems at the moderate and vacuum pressure below the flooding point.

CONCLUSIONS

The hydraulic tests of a structured packing (Sulzer BX) were carried out using the air-water system. A predictive equation for the wet pressure drops, based on the experimental dry pressure drops and liquid holdups, was suggested. Furthermore, the equation was applied to the practical vacuum distillation data. It was found that this predictive equation well correlated the practical vacuum distillation data below the flooding point, but the deviation is sharply increased above the flooding point.

In addition, the effective interfacial areas of Sulzer BX packing were measured, using Danckwerts' model. It was found that the effective interfacial areas of this structured packing increase with the liquid flow rate and are higher than those of sieve tray. It is suggested that this structured packing is efficient in gas-liquid mass transfer.

NOMENCLATURE

A : constant for a given packing type in Eq. (6)
a : effective interfacial area per unit volume of packed column [1/m]
B : base of triangle [m]
C : concentration of dissolved gas in the bulk of liquid [gmol/m^3]

C^* : concentration of dissolved gas at equlibrium with liquid [gmol/m^3]
C_1, C_2 : constants in Eq. (2)
C_3 : constants in Eq. (15)
D : diffusivity of dissolved gas [m^2/s]
d_{eq} : equivalent diameter of packing [m]
f : friction factor based on effective gas velocity
Fr : Froude number for the liquid [$=U_L^2/(d_{eq}\cdot g)$]
F_s : F-factor for superficial vapor flow [$=U_{gs}\cdot\rho_g^{0.5}$, kg$^{0.5}$/m$^{0.5}\cdot$s]
g_c : conversion factor
H : height of triangle (crimp height) [m]
h_{dyn} : dynamic holdup [m^3/m^3]
h_{sta} : static holdup [m^3/m^3]
K : constant in Eq. (14)
K_1 : pseudo first order rate constant [1/s]
K_L : liquid side mass transfer coefficient [m/s]
L : liquid flow rate [m^3/h]
n : exponent for a given packing type in Eq. (6)
P_d : dry pressure drop [Pa/m]
P_w : wet pressure drop [Pa/m]
R : average rate of absorption [gmol/m$^2\cdot$s]
Re_g : Reynolds number for the gas [$=(d_{eq}\cdot U_{ge})/\nu_g$]
Re_L : Reynolds number for the liquid [$=(d_{eq}\cdot L)/\nu_L$]
S : corrugation spacing [m]
T_b : boiling temperature [K]
U_{ge} : effective gas velocity [$U_{gs}/(\varepsilon\cdot\sin\theta)$, m/s]
U_{gs} : superficial gas velocity [m/s]

Greek Letters

ρ_g : density of gas [kg/m^3]
ρ_L : density of liquid [kg/m^3]
μ_g : viscosity of gas [kg/m$\cdot$s]
μ_L : viscosity of liquid [kg/m$\cdot$s]
ν_g : kinematic viscosity of gas [m^2/s]
ν_L : kinematic viscosity of liquid [m^2/s]
ε : void fraction of packing
θ : angle of inclination of flow channel from the horizontal [°]

REFERENCES

Bemer, G. G. and Kalis, G. A. J., *Trans. Instn. Chem. Engrs.*, **56**, 200 (1978).

Billet, R. and Mackowiak, J., "Application of Mordern Packings in Thermal Separation Processes", *Chem. Eng. Technol.*, **11**, 213 (1988).

Billet, R., "Relationship between Residence Time, Fluid Dynamics and Efficiency in Contercurrent Flow Equipment", *Chem. Eng. Technol.*, **11**, 139 (1988).

Bravo, J. L., Rocha, J. A. and Fair, J. L., "Pressure Drop in Structured Packings", *Hydrocarbon Processing*, 45 (March, 1986).

Buchanan, J. E., "Pressure Gradient and Liquid Holdup in Irrigated Packed Towers", *Ind. Eng. Chem. Fundam.*, **8**, 502 (1969).

Cho, S. Y., Choi, D. K. and Lee, Y. Y., "A Study on Improvement of Sieve Tray Performance with Meshed Chamber", *HWAHAK KONGHAK*, **28**, 350 (1990).

Danckwerts, P. V., "Gas-Liquid Reaction", McGraw-Hill, New York, 1962.

Ergun, S., "Fluid Flow through Packed Columns", *Chem. Eng. Progr.*, **48**, 93 (1952).

Fair, J. R. and Bravo, J. L., "Distillation Columns Containing Structured Packing", *CEP*, 19 (Jan., 1990).

Mersmann, A. and Deixer, A., "Packed Columns", *Ger. Chem. Eng.*, **9**, 265 (1986).

Pohorecki, R., "Mass Transfer with Chemical Reaction during Gas Absorption on a Sieve Plate", *Chem. Eng. Sci.*, **31**, 637 (1976).