

Experimental Study on Local Mass Transfer of Structured Packing with the Method of Flow Visualization

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Abstract A chromochemical reactive mass transfer technique has been employed to study local mass transfer characteristics of structured packing. This technology adopted by experiment is an Ammonia Adsorption Method (AAM) that yields the surface distribution of transferred mass by analyzing the color distribution on a filter paper with the results of the color chemical reaction. A digital image processing technology is applied for data visualization. The three-dimensional plot of the local mass transfer coefficients shows that there exist three peak values on different positions of a unit cell of structured packing. In order to improve mass transfer efficiency of the structured packing, one piece of baffle is added between packing sheets. As a result, the average mass transfer coefficient increases by (10–20)% and the pressure drop decreases by (15–55)%.

Keywords local mass transfer, flow visualization, structured packing, baffle

1 INTRODUCTION

BASF [1] first reported the structured packing in 1969. Since then, many hydraulic and mass transfer models have been developed for various structured packings [2–7]. However, those studies were mainly based on the average performances of structured packing [8]. Although MacMurray and Himmelblau [9] employed artificial neural networks to model and describe the packed distillation column, the progress was not substantial. A major prerequisite for better utilization of structured packing is to thoroughly understand its performance at both macro- and micro-scales [10, 11]. Therefore, it is necessary to study the local flow characteristic of structured packing.

Up to date, several methods have been developed to visualize the fluid flow and local mass transfer in structured packing columns. Sogin [12] employed naphthalene as a sublimation medium to determine the local heat transfer based on the analogy between mass and heat transfer. Hallam *et al.* [13] used an electrochemical technique to obtain experimental data of local mass transfer coefficients. Chen *et al.* [14] measured the velocity profiles of single phase flow in structured packing with laser Doppler velocimetry (LDV) at different Reynolds numbers. A comprehensive study by Stasiek *et al.* [15] on the corrugated packing was completed using liquid crystal thermograph, which was more convenient to utilize in heat transfer study. In this work, the chromochemical reactive method by Gerd and Kottke [16, 17] is used because of its easy operation and high accuracy. The photometer is replaced by a scanner with high precision to evaluate the color intensity distribution brought by local mass transfer. Moreover, some new findings on mass transfer in the structured packing are presented.

A lot of studies have been tried to intensify mass

transfer efficiency of structured packing such as opening holes on the surface or changing the configuration of structured packing. Billingham and Lockett [18] reduced the crimp height of structured packing sheets at base to increase the capacity, so it would be available to increase the flow velocity to intensify mass transfer efficiency. However, part of the modified packing sheets could not be probably wetted. Luo *et al.* [19] made a modification of the existing structured packing from triangular flow channels to trapezoid ones based on modifying the channel opening angle. The new structured packing called SCOA with lower pressure drop and higher mass transfer efficiency were investigated both experimentally and numerically, while the effective interfacial area would decrease to some extent because of the trapezoid geometry. Bessou *et al.* [20] even developed a totally new structured packing with high voidage ($\varepsilon = 94\%$), high efficiency area ($a_p = 420 \text{ m}^2 \cdot \text{m}^{-3}$) and high mass transfer efficiency. However, the hydrodynamic performance such as pressure drop and flooding point was lower than the generally used structured packing such as Mellapak 250Y and Mellapak 452Y. In this paper, one new solution is provided to intensify mass transfer efficiency.

2 EXPERIMENTS

2.1 Experimental principle

Based on convective mass transfer and chemical reaction, the Ammonia Adsorption Method (AAM) has been described in detail by Kottke [16, 17]. After soaking in an aqueous solution of manganese(II) chloride (MnCl_2) with hydrogen peroxide (H_2O_2), a wet thin filter paper is coated on the surface of structured packing. Then a tracer gas of ammonia (NH_3) is injected

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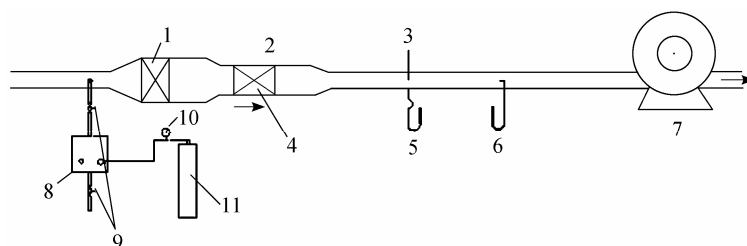


Figure 1 Schematic diagram of the experimental setups

1—static mixer; 2—wind tunnel; 3—thermometer; 4—structured packing; 5—U type manometer; 6—pitot; 7—fan; 8—gas tank; 9—magnetic valve; 10—mamometer; 11—NH₃ in steel cylinder

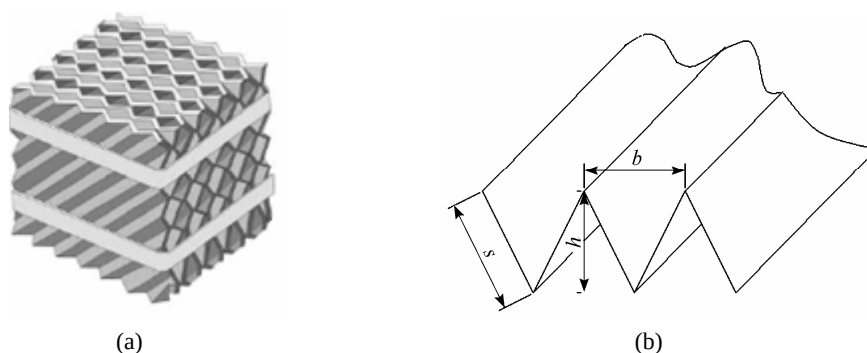


Figure 2 Illustration of (a) a bundle of structured packing and (b) a piece of structured packing

in pulse and partially absorbed by the filter paper. The reaction [21] takes place on the surface of the filter paper.

The resistance of the whole process includes three aspects: phase equilibrium, mass transfer and reaction. Since this reaction is a fast absorption process, the resistance of reaction and the limitation of phase equilibrium can be neglected. The result is a picture with color intensity corresponding to mass density that basically results from mass transfer process. The color intensity is measured by using a scanner (HP ScanJet 4850, Shanghai) and processed by a digital image processing system. At last, the color intensity is replaced by red color value (R) to build up the relationship with surface mass density. [21]

Assume the total time of the pulse of NH₃ is t_1 . During some certain time t , $N_{i,t}$ means the surface mass density on the i th mesh square, and $c_{i,t}$ denotes the concentration of NH₃ in the main stream. Thus, the mass transfer equation can be described by

$$\int_{t=0}^{t_1} N_{i,t} dt = \int_{t=0}^{t_1} k(c_{i,t} - c_w) dt \quad (1)$$

Since this is a fast reaction process, the concentration of NH₃ at the wall c_w is equal to 0, and

$$\int_{t=0}^{t_1} N_{i,t} dt = N_i \quad (2)$$

$$\int_{t=0}^{t_1} c_{i,t} dt = \int_{t=0}^{t_1} c_{0,t} dt = \int_{t=0}^{t_1} \frac{m_t}{V} dt = \frac{m}{V} \quad (3)$$

Combining Eqs. (1), (2) and (3), k can be obtained by Eq. (4).

$$k = \frac{N_i V}{m} \quad (4)$$

where N_i is the surface mass density, which means the total amount of mass transferred onto the i th mesh square of the surface of structured packing, $\text{g} \cdot \text{m}^{-2}$. k is mass transfer coefficient in gas phase, $\text{m} \cdot \text{s}^{-1}$. V is the volume flow rate, $\text{m}^3 \cdot \text{s}^{-1}$. m_t is the mass flow rate, $\text{g} \cdot \text{s}^{-1}$. m is total amount of gas added in the pulse, g . $c_{0,t}$ and $c_{i,t}$ denote the concentration of NH₃ at the entrance and at test section at time t , $\text{g} \cdot \text{m}^{-3}$, respectively.

2.2 Experimental setup

The experimental apparatus is shown in Fig. 1. The wind tunnel is employed to build the calibration curve. Gas flows from left to right, and the flow velocity is measured with a Pitot tube with relative error less than 3.0%. The gas buffer of certain volume provides quantitative injection of reactive gas. The static mixer generates homogeneous flow and uniform concentration of the tracer gas. A bundle of structured packing (see Fig. 2) of $108 \times 108 \times 150 \text{ mm}^3$ is filled in the foursquare test section. Parameters of JKB-250Y structured packing, which is produced by TianDa BeiYang Chemical Equipment Company in Tianjin, are given in Table 1. For experimental purposes, the surfaces of the structured packing are smooth without perforation and shallow embossment.

Table 1 Main parameters of JKB-250Y structured packing

Item	Value
specific surface area $a_p/\text{m}^2\cdot\text{m}^{-3}$	250
void fraction $\varepsilon/\text{m}^3\cdot\text{m}^{-3}$	0.97
corrugation angle $\varphi/(\circ)$	45
channel dimension/m	
height h	0.0120
base b	0.0210
side s	0.0159

2.3 Principle of calibration

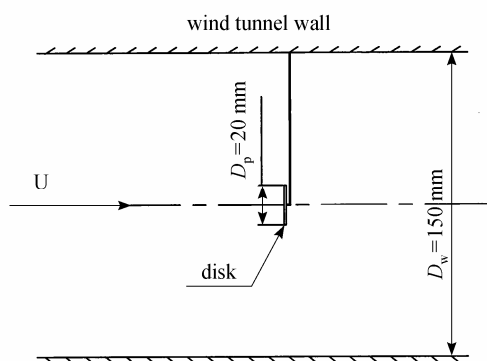
To obtain the mass transfer coefficient, the relation of mass density and color value should be related in advance. The calibration was firstly provided by Sogin [12] with the equipment of wind tunnel, which later became one of the most important calibrating methods [22] in the field of flow visualization. In the range of Reynolds number from 0 to 600,000, an empirical equation was proposed as follows:

$$j\sqrt{\frac{GD_p}{\mu_t}} = 1.08 \quad (5)$$

with a probable error of $\pm 3\%$. In Eq. (5), $j = \frac{k}{u} N_{Sc}^{2/3}$

[12], D_p is the side length of the square disk placed in the center of the wind tunnel.

A piece of wet filter paper with reactants was attached on the foursquare disk of $20 \times 20 \text{ mm}^2$ in wind tunnel (see Fig. 3). Reaction happened when certain amount of gas passed through the paper, and the product with color (R) would be obtained. Then the corresponding surface mass density (N) could be calculated according to Eqs. (4) and (5). The relationship of N and R could be obtained by changing the amount of NH_3 .

**Figure 3** Schematic diagram of the wind tunnel and the disk

It should be noted that the calibration process and experiments on structured packing were two separate parts. The wind tunnel with the disk was for calibration. Then the wind tunnel was replaced by foursquare

test section filled with structured packing (shown in Fig. 1) to continue to study on the local mass transfer of structured packing.

3 RESULTS AND DISCUSSION

3.1 Calibration equation

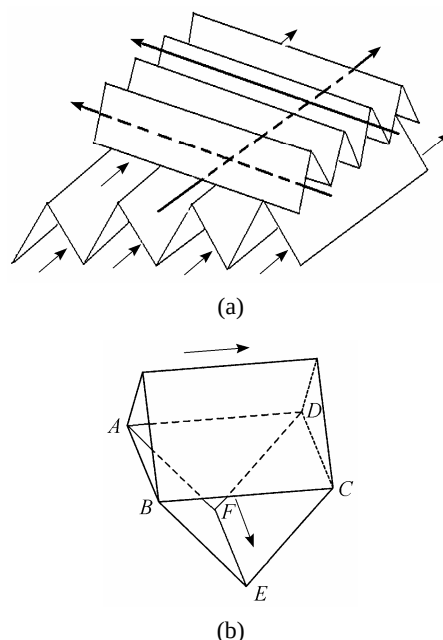
By changing the concentration of the NH_3 when F -factor = 1.6, $T = 298 \text{ K}$, $p = 101.325 \text{ kPa}$, series of N and R have been attained. The calibrating equation is fitted as follows:

$$N = A \exp(-R/B) + C \quad (6)$$

where $A = 2.624$, $B = 106.2$, and $C = -0.24$. When the structured packing is tested, the mass transfer coefficient can be obtained by Eqs. (4) and (6).

3.2 Local mass transfer coefficients

The flow physical model shown in Fig. 4 (a) consists of some unit cells, one of which is shown in Fig. 4 (b). Directions of arrowheads denote directions of fluids. Three-dimensional plot of mass transfer coefficients of the unit cell is shown in Fig. 5 when F -factor = 2. It shows that there are three areas with peak values. The first area with highest peak value is around the crosspoints A , B , C and D , and the second one, which parallels with the crest CD , is on the windward face $FECD$. The lowest peak value also lies on the leeward paralleling with the trough EF .

**Figure 4** Illustration of (a) geometry of unit cells and (b) a unit cell

These phenomena described above can be explained as follows. It is known that at the inclination

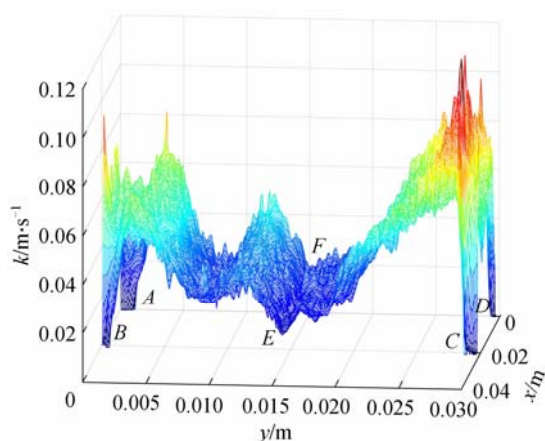


Figure 5 Three-dimensional plot of mass transfer coefficients in a unit cell (F -factor = 2)

angle of 45° , the fluid flows mainly along the tunnel [23]. The fluid flowing along the upper tunnel from left to right accelerates and rushes straight on the surface $FECD$. Because of fast surface regeneration, the mass transfer rate is high. While a part of the fluid flows across the crest CD to the next unit, the other part comes back and meets the fluid flowing along the lower tunnel from F to E . The total effect of these two flows generates the mass transfer peak near the trough EF by thinning the boundary layer. Due to the narrow flow space, the two cross streams are both considerably accelerated around the crosspoints of A , B , C and D , where intense turbulence and swirling flow appear, resulting in high mass transfer efficiency.

3.3 Influence of adding baffle between packing sheets

According to the flow behavior discussed above, one piece of baffle is added between two pieces of structured packing as shown in Fig. 6. Three-dimensional plot of mass transfer coefficients of the same unit cell is presented in Fig. 7. As expected, the result clearly proves that the approach really intensifies the mass transfer especially in the trough of the unit cell.

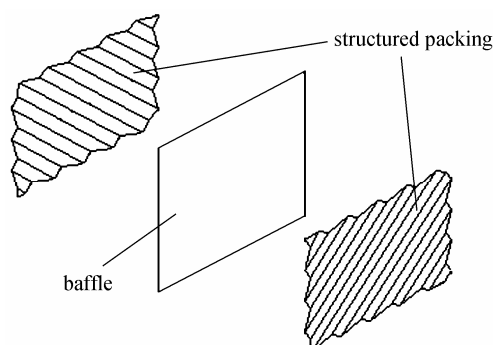


Figure 6 Structural diagram of adding baffle between packing sheets

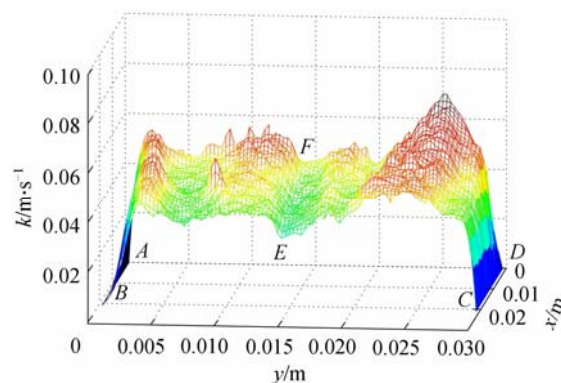
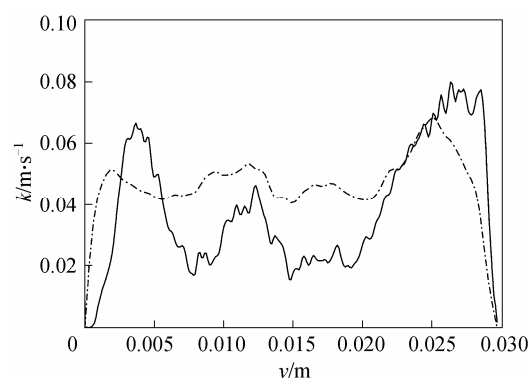
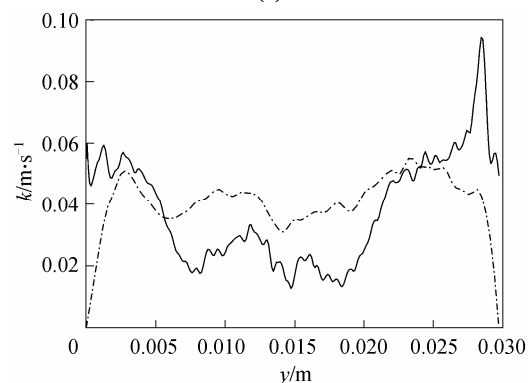


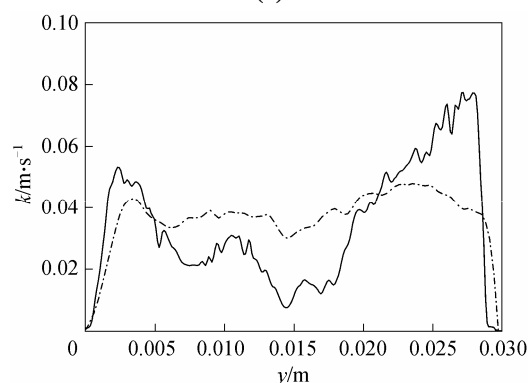
Figure 7 Three-dimensional plots of mass transfer coefficients with baffle (F -factor = 2)



(a)



(b)



(c)

Figure 8 Values of mass transfer coefficient of (a) $x = 0$ (b) $x = 0.0105$ mm (c) $x = 0.021$ mm
— before adding baffle; ---- after adding baffle

To better offer the performance of adding baffle, specific values of mass transfer coefficient at every point are compared between with and without baffle. Figs. 8 (a)–(c) show the difference at different x location along y direction. It is obviously that mass transfer efficiency is enhanced well. Values at the cross points A , B , C and D without baffle as well as at the lines AB and CD are quite small. It is because that the points represent the tight contact parts between filter paper and the packing sheets, where there is almost no reaction.

The average mass transfer coefficient and pressure drop are compared between two methods under different F -factors in Figs. 9 and 10. It shows that the average mass transfer coefficient increases by (10–20)% and the pressure drop decreases by (15–55)%.

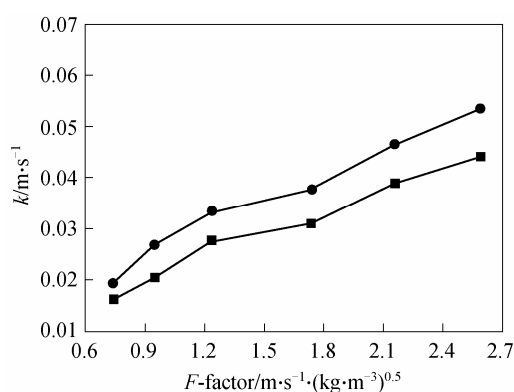


Figure 9 Comparison of mass transfer coefficients between with and without baffle

■ before adding baffle; ● after adding baffle

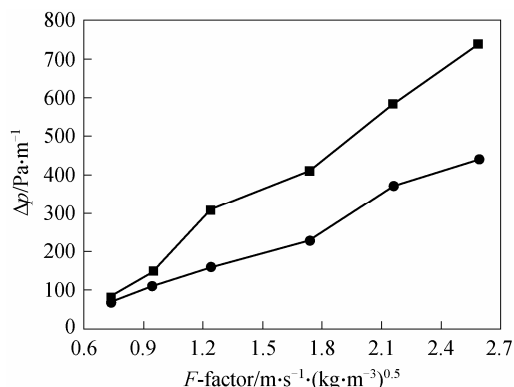


Figure 10 Comparison of pressure drop between with and without baffle

■ before adding baffle; ● after adding baffle

Adding baffle can improve the performance of structured packing, while some disadvantages will happen if the liquid flow is taken into consideration. The liquid might flow along the baffle replacing the structured packing. Therefore, some further research on modifying the configuration of the baffle should be carried out.

4 CONCLUSIONS

By utilizing the chromochemical reactive method, the local mass transfer of structured packing has been visualized and measured. The test samples have been dealt with in such a high currency that the unit mesh is about 0.016×0.016 mm. In the three-dimensional plot of mass transfer coefficients in each unit cell, it has been clearly shown that there exist three areas with intensification of mass transfer.

One piece of baffle is added between two pieces of structured packing due to the asymmetrical mass transfer distribution in the unit cell. After adding the baffle, mass transfer efficiency improves and pressure drop largely decreases. However, adding the baffle will reduce the opportunity that liquid phase wet the structured packing. Therefore, further research is needed to explore this solution.

NOMENCLATURE

a_p	specific surface area of packing, $\text{m}^2 \cdot \text{m}^{-3}$
b	corrugation base length, m
c_i	concentration of NH_3 at test section, $\text{g} \cdot \text{m}^{-3}$
c_0	concentration of NH_3 at the entrance, $\text{g} \cdot \text{m}^{-3}$
D	diffusivity of vapor in air, $\text{m}^2 \cdot \text{s}^{-1}$
D_p	diameter of the disk, m
D_w	diameter of the wind tunnel, m
F -factor	$F = u\sqrt{\rho}$, $\text{m} \cdot \text{s}^{-1} \cdot (\text{kg} \cdot \text{m}^{-3})^{0.5}$
G	mass velocity of gas, $\text{kg} \cdot \text{s}^{-1}$
h	corrugation height, m
j	j factor ($j = kN_{\text{Sc}}^{2/3}/u$)
k	mass transfer coefficient, $\text{m} \cdot \text{s}^{-1}$
m	total amount of gas added in the pulse, g
m_t	mass flow rate, $\text{g} \cdot \text{s}^{-1}$
N	local surface density in the whole process, $\text{g} \cdot \text{m}^{-2}$
N_i	the surface density in the i th square, $\text{g} \cdot \text{m}^{-2}$
N_{Sc}	Schmidt number ($N_{\text{Sc}} = u/\rho D$)
p	pressure, Pa
R	digital value of red color
T	temperature, K
t	time, s
u	fluid velocity, $\text{m} \cdot \text{s}^{-1}$
V	volume flow rate, $\text{m}^3 \cdot \text{s}^{-1}$
x, y	Cartesian coordinates, m
ε	void fraction, $\text{m}^3 \cdot \text{m}^{-3}$
μ	dynamic viscosity, $\text{Pa} \cdot \text{s}$
μ_t	dynamic viscosity of mean film, $\text{Pa} \cdot \text{s}$
ρ	void fraction, $\text{m}^3 \cdot \text{m}^{-3}$
φ	inclination angle of the corrugation, ($^\circ$)

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