

## Mass transfer between a fluid and an immersed object in liquid–solid packed and fluidized beds

NEVENKA BOŠKOVIĆ-VRAGOLOVIĆ, DANICA BRZIĆ and ŽELJKO GRBAVČIĆ

Faculty of Technology and Metallurgy, Department of Chemical Engineering, University of Belgrade, Karnegijeva 4, 11000 Belgrade, Serbia and Montenegro  
(e-mail: grbavcic@elab.tmf.bg.ac.yu)

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*Abstract:* The mass transfer coefficient between fluid and an immersed sphere in liquid packed and fluidized beds of inert spherical particles have been studied experimentally using a column 40 mm in diameter. The mass transfer data were obtained by studying the transfer of benzoic acid from the immersed sphere to flowing water using the dissolution method. In all runs, the mass transfer rates were determined in the presence of inert glass particles 0.50–2.98 mm in diameter. The influence of different parameters, such as: liquid velocity, particles size and bed voidage, on the mass transfer in packed and fluidized beds is presented. The obtained experimental data for mass transfer in the packed and particulate fluidized bed were correlated by a single correlation, thus confirming the similarity between the two systems.

*Keywords:* mass transfer, packed beds, particulate fluidized beds, correlation.

### INTRODUCTION

In the past research of transport phenomena in liquid–particles systems, had a more theoretical than a practical importance. Due to their employment in industry, especially with the fast development of bio and water cleaning processes, a better knowledge of these systems become more important. Industrial application of these systems requires the determination of the transfer characteristics, especially mass transfer. Liquid–solid packed and fluidized beds have usually been investigated separately,<sup>1–5</sup> but many authors have noticed the similarity between the two systems.<sup>6</sup>

Flow of fluid through packed beds is usually described by the capillary theory, according to which, fluid flows through irregular channels. In packed beds, the mass transfer coefficient is in the following relationship:<sup>7</sup>

$$\frac{(k_c / u) Sc^{2/3}}{(ud_H \rho / \mu)^m} = const. \quad (1)$$

The hydraulic diameter for beds of spherical particles is:  $d_H = \epsilon d_p / (1 - \epsilon)$  and the interstitial velocity is:  $u = U/\epsilon$ , hence:

$$(k_c/U)\epsilon Sc^{2/3} = \text{const.} \left[ \frac{U d_p \rho}{\mu(1 - \epsilon)} \right]^{-m} \quad (2)$$

or:

$$j_D \epsilon = \text{const.} \left( \frac{Re_p}{1 - \epsilon} \right)^{-m} \quad (3)$$

In this study it was shown that relationship (3) is valid for particulate fluidized beds as well as for packed beds.

#### EXPERIMENTAL

The rates of mass transfer between a fluid and an immersed sphere in packed and fluidized beds of spherical inert particles were studied. The schematic diagram of the experimental system is shown in Fig. 1.

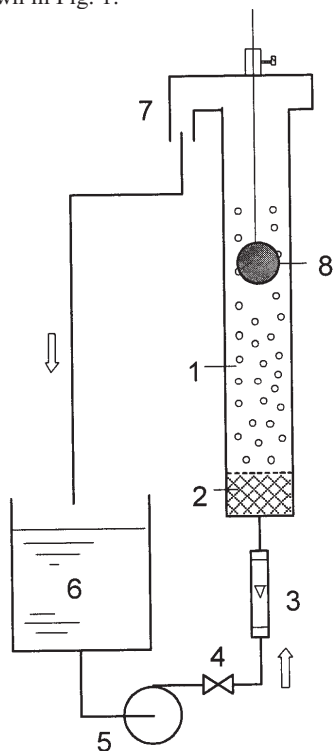


Fig. 1. Schematic diagram of the experimental system: 1-column, 2-distributor, 3-flowmeter, 4-valve; 5-pump, 6-tank, 7-overflow, 8-immersed sphere.

The experiments were conducted using a column  $D_c = 40$  mm in diameter and water as the fluidizing fluid. Dissolution of benzoic acid from a large single sphere ( $D_p = 21$  mm) was followed. Coating was performed by immersing a sphere ( $D_p = 20$  mm) on a wire support in molten benzoic acid. By repeating the procedure, a compact layer of benzoic acid was formed on the sphere. The fi-

nal form was adjusted to  $D_p = 21$  mm using a specially designed rotating knife. The mass transfer coefficient was calculated from the equation:

$$k_c = \frac{\Delta m}{At\Delta c} = \frac{\Delta m}{(D_p^2 \pi) t \Delta c} \quad (4)$$

The transferred mass  $\Delta m$  was determined by measuring the weight loss of benzoic acid. The mass transfer area  $A$  was calculated considering the mean value of the sphere diameter before and after dissolution. Since the weight loss of benzoic acid  $\Delta m$ , was small, the bulk concentration was negligible, hence the equilibrium concentration,  $c^*$  was taken as the driving force  $\Delta c$ .

Benzoic acid solubility and diffusivity in water were taken from the literature.<sup>8,9</sup> In each run, the average fluid temperature was recorded and the corresponding values of the diffusion coefficients, fluid viscosity, fluid density and equilibrium solubility were taken for the calculations. The important properties of the fluid, particles and bed are summarised in Table I.

Measurements in packed beds were conducted by using loosely and densely packed beds. The sphere was inserted at a fluid velocity slightly above the minimum fluidization velocity and then the fluid velocity was stopped. The dense bed was additionally vibrated. In all runs, the start-up procedure required less than 30 s, which is negligible with respect to the time of exposition, which was typically about 20 min.

The voidages of loosely and densely packed beds are given in Table II.

TABLE I. Particle and fluid characteristics

Particles (glas spheres)				
$d_p/\text{mm}$	$\rho_p/\text{kg m}^{-3}$	$\epsilon_{mf}$	$U_{mf}/\text{m s}^{-1}$	$U_t/\text{m s}^{-1}$
0.54	2479	0.414	0.0037	0.087
0.68	2674	0.392	0.0052	0.119
0.803	2923	0.398	0.0083	0.154
1.2	2641	0.392	0.0129	0.208
1.94	2507	0.4215	0.0255	0.299
2.98	2509	0.462	0.0435	0.371
Fluid (water at 25 °C)				
$\rho/\text{kg m}^{-3}$	$\mu/\text{Pa s}$	$D/\text{m}^2\text{s}^{-1}$	$c^*/\text{kg m}^{-3}$	$Sc$
977	$0.893 \times 10^{-3}$	$9.24 \times 10^{-10}$	3.3554	969

TABLE II. Voidage of packed beds

Packed mode	Voidage
Loose packed	0.43–0.47
Dense packed	0.32–0.37

## RESULTS AND DISCUSSION

The mass transfer coefficients in the packed and fluidized beds as a function of the interstitial fluid velocity are shown in Fig. 2. The data for the mass transfer coefficients for liquid flow around the sphere (without particles) are shown in the same plot for comparison. The experimental data show that:

– The mass transfer in the presence of particles is more intensive, hence the values of the mass transfer coefficient are greater in both the two-phase systems (packed and fluidized bed) than with liquid flow around a single sphere. When the liquid flows around a single sphere only one part of the area is exposed to transfer. In the presence of particles the whole area become active and the boundary layer become thinner, thus increasing the mass transfer.

– With increasing liquid velocity in the packed beds, the mass transfer coefficient increases without the strong influence of bed voidage. The influence of the particle diameter of the mass transfer can be clearly seen. With decreasing particle size, the diameter of the channels decreases, which increases the interstitial velocity and thus the mass transfer coefficient.

– With increasing interstitial velocity in the fluidized bed, the mass transfer coefficient decreases slightly reaching the value of the mass transfer coefficient for flow around a single sphere.

The mass transfer as a function of the Reynolds number of the particles in packed and fluidized beds are presented in Fig. 3. As can be seen, the mass transfer factor ( $j_D$ ) in packed beds is independent of particle size. The data for the mass transfer factor in fluidized beds can be separated into two groups, depending on the particle diameter. The data for each group fall on straight lines, the slopes of which are approximately the same but different from that for the packed beds.

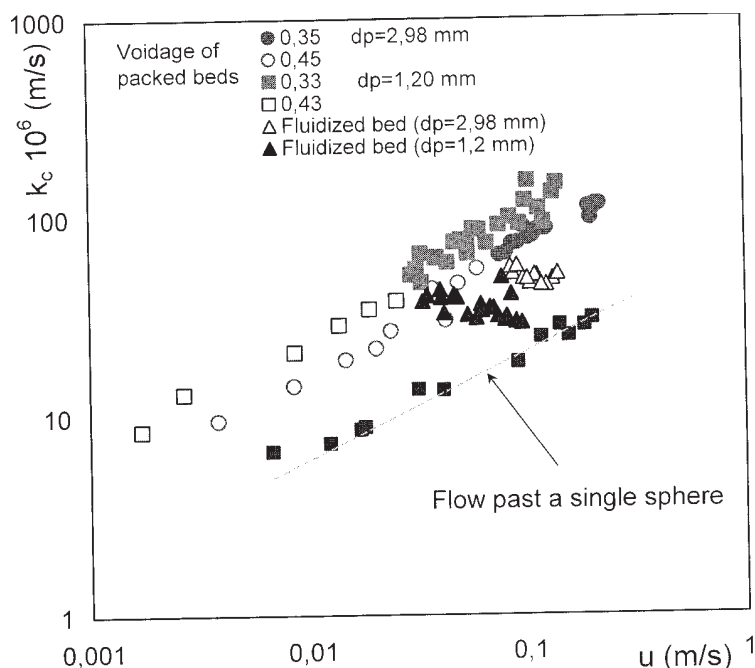


Fig. 2. Mass transfer coefficient vs. interstitial fluid velocity for packed and fluidized beds and for liquid flow around a sphere.

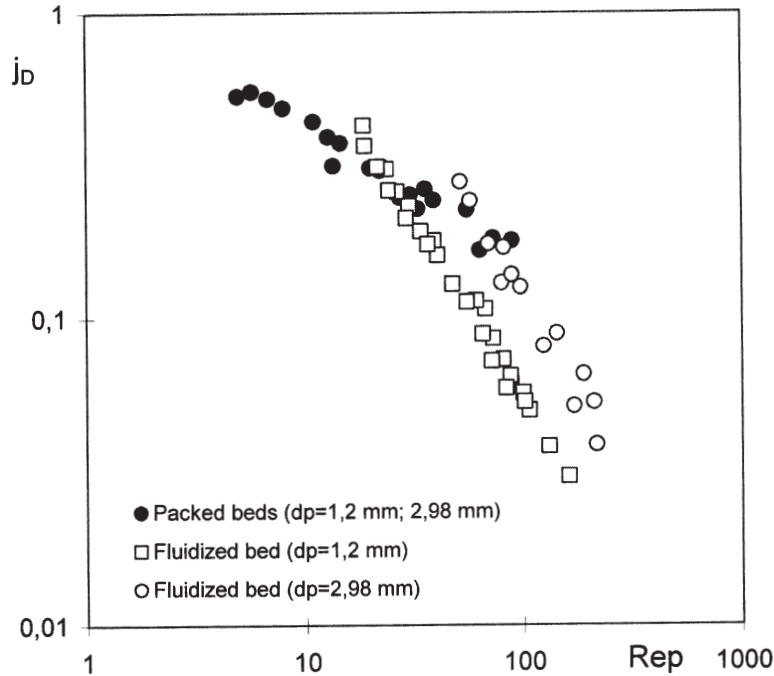


Fig. 3. Relationship between  $j_D$  and Reynolds number of the particles in packed and fluidized beds.

Although  $k-u$  and  $j_D-Re_p$  dependences show different trends for packed and fluidized beds, correlating all the data together in the form  $j_D \epsilon$  vs.  $Re_p/(1-\epsilon)$  shows a single trend expressed through the following correlation:

$$j_D \epsilon = 0.64 \left( \frac{Re_p}{1-\epsilon} \right)^{-0.4} \tag{5}$$

with a mean absolute deviation of 16.88 % and a mean relative deviation of -3.71 %.

The fact that the mass transfer coefficients for packed and fluidized bed can be correlated with a single equation confirms the existence of mass transfer similarity in these systems.<sup>6</sup> This result is interesting because it shows the transfer similarity in two different systems: one with fixed particles and the other with moving particles.

#### CONCLUSIONS

Experiments were performed to determine the mass transfer coefficient between a fluid and an immersed sphere in liquid packed and fluidized beds of inert particles. The results show that:

- 1) With increasing liquid velocity, the mass transfer coefficient:
  - increases in packed beds

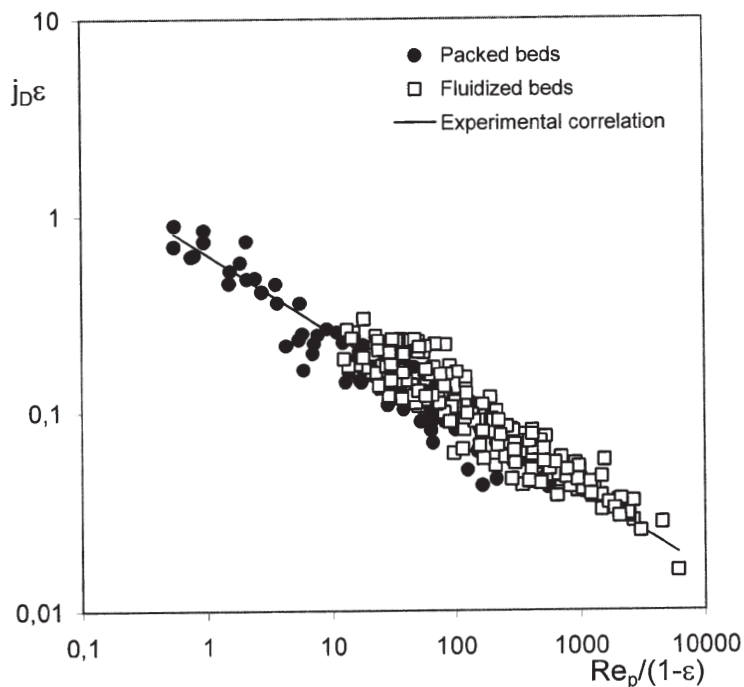


Fig. 4. Experimental correlation.

– slightly decreases in fluidized beds.

2) The mass transfer factor as a function of the Reynolds number of the particles:

- is independent of particle size, but it depends on the packing mode in packed beds
- depend on the particle size in fluidized beds.

New correlations for the mass transfer factor in packed and fluidized beds are proposed.

#### LIST OF SYMBOLS

- $A$  – Mass transfer area,  $m^2$   
 $c^*$  – Equilibrium concentration of benzoic acid in water,  $kg/m^3$   
 $\Delta c$  – Concentration difference (driving force),  $kg/m^3$   
 $D$  – Molecular diffusion coefficient,  $m^2/s$   
 $D_c$  – Column diameter,  $m$   
 $D_p$  – Test sphere diameter,  $m$   
 $d_H$  – Hydraulic diameter,  $m$   
 $d_p$  – Particle diameter,  $m$   
 $j_D$  – Mass transfer factor,  $(kSc^{2/3}/U)$   
 $k_c$  – Mass transfer coefficient,  $m/s$   
 $\Delta m$  – Total mass transferred,  $kg$   
 $Re_p$  – Reynolds number of the particles ( $d_p \rho U / \mu$ )  
 $Sc$  – Schmidt number,  $(\mu / \rho D)$   
 $t$  – Exposure time,  $s$

$U$  – Superficial fluid velocity, m/s  
 $U_{mf}$  – Minimum fluidization velocity, m/s  
 $U_t$  – Terminal velocity, m/s  
 $u$  – Interstitial fluid velocity, m/s

*Greek letters*

$\varepsilon$  – Bed voidage  
 $\varepsilon_{mf}$  – Bed voidage at minimum fluidization  
 $\mu$  – Fluid viscosity, Pa s  
 $\rho$  – Fluid density, kg/m<sup>3</sup>  
 $\rho_p$  – Particle density, kg/m<sup>3</sup>

ИЗВОД

ПРЕНОС МАСЕ ФЛУИД–УРОЊЕНИ ОБЈЕКАТ У ПАКОВАНИМ И  
 ФЛУИДИЗОВАНИМ СЛОЈЕВИМА ТЕЧНОСТ–ЧЕСТИЦЕ

НЕВЕНКА БОШКОВИЋ-ВРАГОЛОВИЋ, ДАНИЦА БРЗИЋ И ЖЕЉКО ГРБАВЧИЋ

*Технолошко-механички факултет, Катедра за хемијско инжењерство, Универзитет у Београду,  
 Карнегијева 4, 11000 Београд*

У овом раду је експериментално испитиван прелаз масе између уроњене сфере и флуида у присуству пакованих и флуидизованих честица. За одређивање коефицијента прелаза масе коришћена је метода праћења растварања слабо растворне супстанце-бензоеве киселине у води. Коришћена је колона пречника 40 mm, уроњена сфера пречника 21 mm, а паковане и флуидизоване слојеве су чиниле стаклене сфере пречника 0,5–2,98 mm. Испитивања у пакованим слојевима извршена су у системима са различитим паковањима – ретком и густом. Приказани су утицаји различитих параметара, као што су брзина флуида, величина честица и порозност слојева на коефицијент прелаза масе. Показане су разлике и сличности у преносу масе када су у слоју присутне непокретне и флуидизоване честице. Дата је завршна експериментална корелација која је заједничка и за паковане и за флуидизоване слојеве. Корелација је дата као веза бездимензионих група  $Re_p/(1-\varepsilon)$  и  $j_D\varepsilon$  које нису типичне за корелисање података у флуидизованим слојевима. Ова корелација указује да постоји сличност механизма преноса масе у пакованим и партикулативно флуидизованим слојевима.

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REFERENCES

1. S. Kumar, S. N. Upadhyay, *Ind. Eng. Chem. Fundam.* **20** (1981) 186
2. Yutani, N. Ototake, L. T. Fan., *Ind. Eng. Chem. Res.* **26** (1987) 343
3. J. Comiti, M. Renaud, *Chem. Eng. Sci.* **46** (1991) 143
4. N. Bošković-Vragolović, Ž. Grbavčić, D. Janković, V. Minić, *J. Serb. Chem. Soc.* **61** (1996) 401
5. S. Schmidt, J. Buchs, C. Born, M. Biselli, *Chem. Eng. Sci.* **54** (1999) 829
6. P. N. Dwivedi, S. N. Upadhyay, *Ind. Eng. Chem. Proc. Des. Dev.* **16** (1077) 157
7. W. J. Beek, *Fluidization Davidson & Harrison, Academic Press, London and New York, 1971, p. 431*
8. S. Kumar, N. S. Upadhyay, *Ind. Eng. Chem. Fundam.* **19** (1980) 75
9. S. Kumar, N. S. Upadhyay, K. V. Mathur, *J. Chem. Eng. Data* **23** (1978) 139.