

Mass Transfer At Helical Coils In Bubble Columns

S. A. Nosier and Mousa M. Mohamed*

Chemical Engineering Department, Faculty of Engineering,
Alexandria University, Egypt.

*Mechanical Power Engineering Department,
Faculty of Engineering Minufiya University, Egypt.

Original scientific paper
Received: March 4, 2003
Accepted: March 15, 2004

Mass transfer rates at the outer surfaces of helical coil were studied by measuring the rate of diffusion-controlled dissolution of a helical copper coil in acidified chromate solution. Variables studied were; air superficial velocity, solution temperature and the number of active rings per coil. The mass transfer coefficient was found to increase with increasing airflow rate. Increasing the number of active rings per coil decrease the mass transfer coefficient. The mass transfer data were correlated by the equation:

$$J = 0.778(Fr \cdot Re)^{-0.263} \left(\frac{d_t}{l_w} \right)^{0.245}$$

Keywords:

Mass transfer; bubble columns; solid-liquid; helical coil; diffusion controlled; gas sparging.

Introduction

Helical coils are frequently used for transferring heat in reactor vessels, in mixing tanks and in bubble columns. Such coils can also be used to improve mass transfer rates as in membrane blood oxygenators,¹ in kidney dialysis devices² and in reverse osmosis units.³ In view of this practical importance of tubular coils some work has been done on the heat, mass, and momentum transfer characteristics of tubular coils under forced convection conditions.^{1–11} Little work has been reported on the forced convection mass transfer characteristics of the outer surfaces of helical coils in bubble column. A large number of the heterogeneous reactions carried out in bubble columns are highly exothermic, and temperature control optimum is essential to obtain a high yield. Also, in bioreactors, both, intensive heat supply for thermal sterilization of the medium and heat removal from microbial reactions imply a correct construction of heat transfer areas. Heat exchange via the reactor wall is not always possible, so additional heat exchange facility like helical coils are installed in bubble columns and gas sparged reactors. Knowledge of heat transfer rates between the gas-liquid dispersion and the heating or cooling surface is essential for the rational design of the helical coil heat exchanger.

The aim of the present work is to study liquid-solid mass transfer at helical coils by measuring the diffusion-controlled dissolution of the copper coils in acidified chromate solution. This technique has been frequently used to study liquid-solid mass transfer in view of its simplicity and accuracy.¹²

The study of solid-liquid mass transfer in bubble columns would make it possible to predict the rate of diffusion-controlled processes that may occurs at the surfaces of the helical coils, e.g. diffusion controlled corrosion, diffusion controlled biochemical reaction taking place on immobilized enzymes fixed on the coils and liquid-solid diffusion controlled catalytic reactions taking place on a solid catalyst supported on the coils. Besides, in view of the analogy between heat and mass transfer, the present mass transfer study can be also used to predict the approximate heat transfer coefficient at the surface of the helical coil, that can be used as a heat exchanger beside being a catalyst supporting surface. The dual role of using helical coils as a catalyst supporting surface and a heat exchanger would improve the economy of bubble column and gas sparged reactors. Heat exchangers are essential part of bubble columns and gas sparged reactors where exothermic or endothermic reactions are conducted in order to control the column temperature at the optimum value.

The present work aims also to compare the present data and the previous data obtained for arrays of straight tubes in the area of mass transfer.

Experimental

The experimental setup is shown in Fig. 1. It consisted of a glass cylindrical column of diameter 7.9 cm and height 50 cm. The column was fitted at its bottom with a G4 sintered glass distributor of

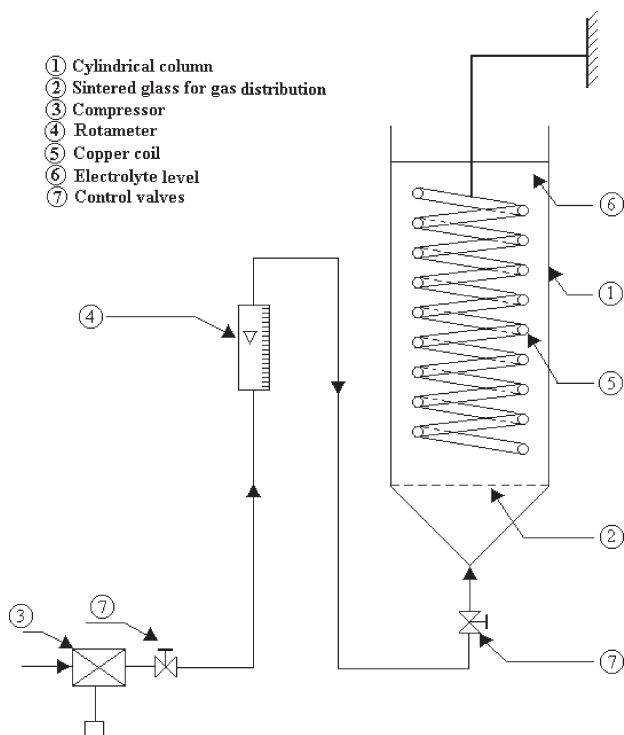


Fig. 1 – Schematic of experimental apparatus

7 cm diameter and is 0.5 cm thick. The average diameter of the pores of sintered distributor was 5–10 microns. A copper coil was placed vertically in the column and mounted centrally 10 cm above the distributor. One helical coil of copper of ring, diameter 4.7 cm, tube diameter of 0.3 cm and of pitch 0.84 cm, were used. The number of rings per coil was 17. Before each run, the coil was treated with fine emery paper to remove any surface roughness and washed thoroughly with distilled water and dried. For each run 1250 cm³ of fresh K₂Cr₂O₇/H₂SO₄ solution were carefully introduced to avoid mixing as far as possible before air stirring. In the meantime air was allowed to flow through the column. The airflow rate was controlled by a regulator and measured by a calibrated rotameter. 5 ml samples were withdrawn at 5 min intervals for chromate analysis by titration against standard ferrous ammonium sulfate using diphenylamine indicator.¹³ The superficial air velocity was measured and varied from 0.4011 to 4.814 cm s⁻¹. Experiments were carried out at a temperature range from 18 to 28.5 °C. The solution used in this study was 0.003 mol dm⁻³ K₂Cr₂O₇ + 0.5 mol dm⁻³ H₂SO₄. The solution was prepared using A.R grade chemicals and distilled water. The active number of turns per coil studied in the present work was 5, 7, 9 and 11, respectively. Insulating part of it with Teflon tape controlled the active number of turns per coil. Viscosity and density of the solution were used in the present data correlation, measured by an Ostwald viscometer

and a density bottle, respectively.¹⁴ The diffusivity of dichromate was calculated from literature values,¹⁵ and was corrected for temperature change using the Stokes-Einstein equation.

Results and discussion

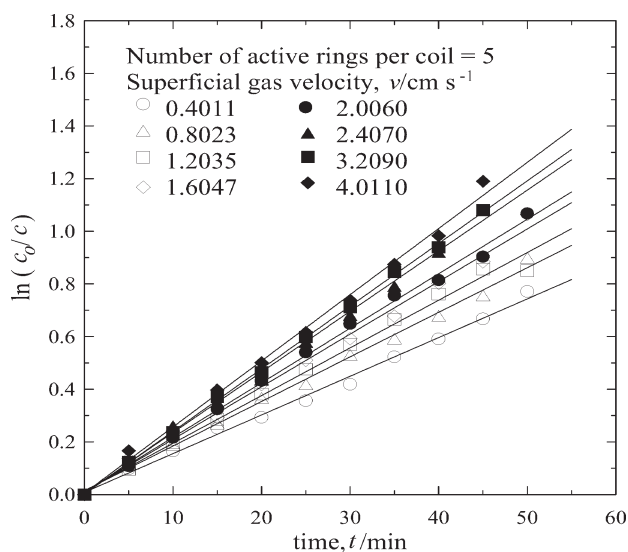
The rate of diffusion-controlled reaction between the acidified chromate and the copper coil by the equation:

$$-Q \frac{dc}{dt} = k A c \quad (1)$$

which upon integration yields,

$$\ln c_0/c = k A t/Q \quad (2)$$

Fig. 2 shows typical $\ln c_0/c$ vs. t plots made for different air superficial velocities. The solid-liquid mass transfer coefficient was obtained for different conditions of air superficial velocity and the number of active ring per coil from the slope of $\ln c_0/c$ vs. t .

Fig. 2 – $\ln c_0/c$ versus t at different superficial gas velocities

An empirical mass transfer correlation was obtained in terms of the dimensionless groups, J , Re and Fr , usually used in correlating heat and mass transfer data in bubble columns. Physical properties of the solution were used to calculate, both, Sc and Re numbers. An extra dimensionless factor (d_t/l_w) was found necessary to account for the effect of the working section length. The helical tube diameter was used as a characteristic length in calculating Re . Fig. 3 shows that for the conditions: $880 < Sc <$

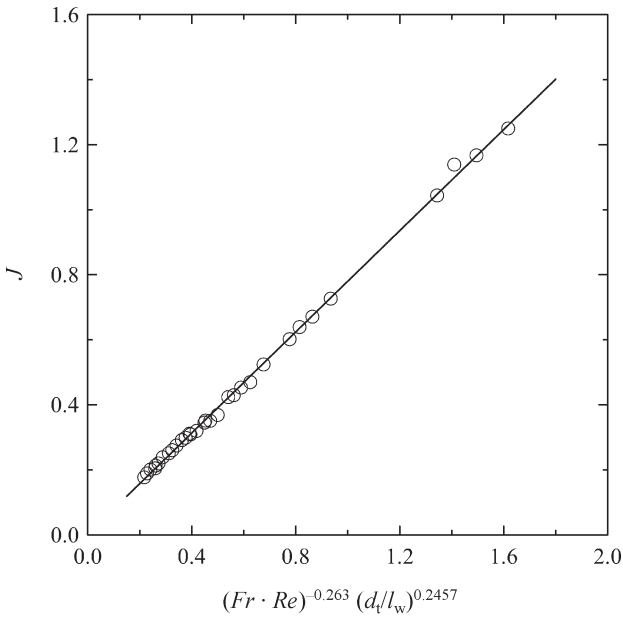


Fig. 3 – Overall mass transfer correlation

1100, $0.0129 < Fr \cdot Re < 12.9852$ and $0.0314 < d_t/l_w < 0.0667$ The appropriate equation is:

$$J = 0.778(Fr \cdot Re)^{-0.263} \left(\frac{d_t}{l_w} \right)^{0.245} \quad (3)$$

with an average deviation of $\pm 2.16 \%$.

The existence of the (d_t/l_w) ratio in the overall mass transfer correlation may throw some light on the mass transfer mechanism: (i) the bubble swarm induces radial momentum transfer which brings a fresh supply of the liquid reactant to the solid surface (surface renewal model);¹⁶ (ii) the turbulence which may result from bubble coalescence or breakdown, collision bubbles with the helical coil surface, or in the wake regions of rising bubbles lead to disturbance of the diffusion layer (hydrodynamic model). According to the first model (i) the working section length (l_w) does not affect k , but according to the second model (ii) the working section length has a significant effect on k . Thus it seems that the two mechanisms contribute to enhancing the rate of mass transfer at the helical coil surface.

Similar results to our findings were obtained by *Bohm et al.*¹⁹ in their study of liquid to wall mass transfer in bubble column, all the experimental data were correlated by introducing the geometric factor (L/D_e) where L is the electrode length and D_e is the column diameter.

Fig. 4 shows that the mass transfer coefficient is related to the superficial gas velocity by the equation:

$$k = a_1 Re^{0.229} \quad (4)$$

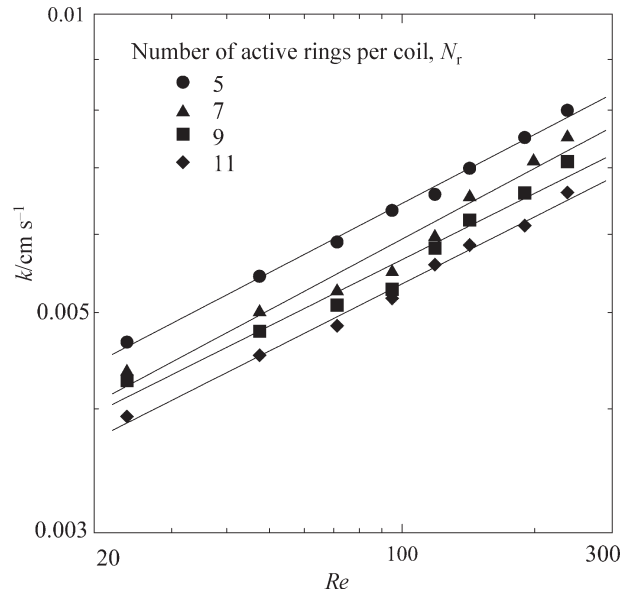


Fig. 4 – k versus Re at different number of active rings per coil

The increase in (k) with the air flow rate may be attributed to the following effects: (i) the rising bubbles generate turbulence in their wakes by virtue of hydrodynamic boundary layer separation; (ii) bubble coalescence or breakdown in the vicinity of the tube surface generates turbulence which penetrates the diffusion layer; (iii) collision of the rising bubbles with the front surface of the helical coil disturbs the diffusion layer with a consequent increase in the rate of mass transfer; (iv) the swarm of rising bubbles imparts radial momentum to the surrounding fluid.¹⁷

Fig. 5 shows that the effect of the working section length represents the active rings and the clearance between these rings on the mass transfer J factor at different superficial air velocity. The data are shown to fit the equation:

$$J = a_2 l_w^{-0.246} \quad (5)$$

The decrease in (k) with increasing working section length may be attributed to the progressive local decrease in $K_2Cr_2O_7$ mass concentration below the bulk value as the solution moves upward past different rings. It seems that the presence of the helical coil in the bubble column diminishes back mixing in a manner similar to packing material in case of packed.¹⁸ As a consequence, replenishment of the reacted solution with fresh $K_2Cr_2O_7$ from the bulk solution is hindered by the lack of sufficient back mixing. This phenomena was supported by *Bohm et al.*¹⁹ who studied the effect of gas sparging on the rate of mass transfer from the wall of vertical tube, *Lewis et al.*²⁰ who studied the effect of heater length on the heat transfer coefficient in bub-

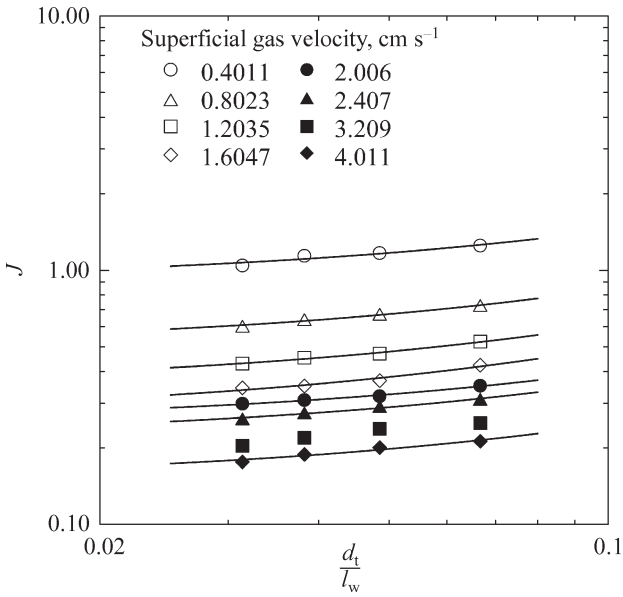


Fig. 5 - Effect of the ratio (d_t/l_w) on the mass transfer J factor at different superficial gas velocities

ble columns and Sultan et al.²² who studied the effect of gas sparging on the recovery of Cu^{++} from industrial wastes by electrochemical technique using vertical plate and fixed beds of cylinders and Raschig rings.

The decrease in (k) with increasing number of active rings observed in the present work as shown in Fig. 6, may be explained in a manner similar to that used in explaining the effect of the working section height.

To throw some light on the role played by tube curvature on the rate of mass transfer, the present

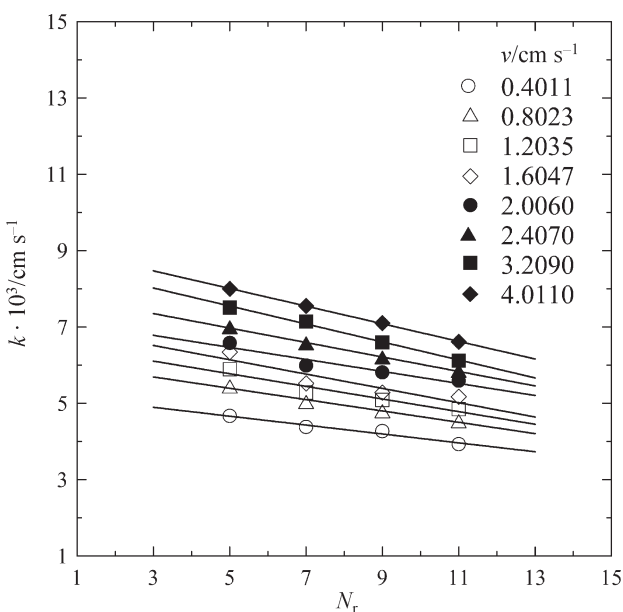


Fig. 6 - Effect of the number of active rings per coil on the mass transfer coefficient at different superficial gas velocity

data for helical coils were compared with the mass transfer data obtained by Nosier,²¹ who studied the solid-liquid mass transfer at gas sparged tube bundles under the conditions: $850 < Sc > 1370$, $0.0021 < Fr \cdot Re < 0.1603$, $1 < N_r > 5$ (cf. Fig. 7), where N_r is the number of rows. The increasing in the mass transfer coefficient may be ascribed partly to the fact that the presence of helical coils decreases the axial dispersion (back mixing) compared to array of straight tubes.

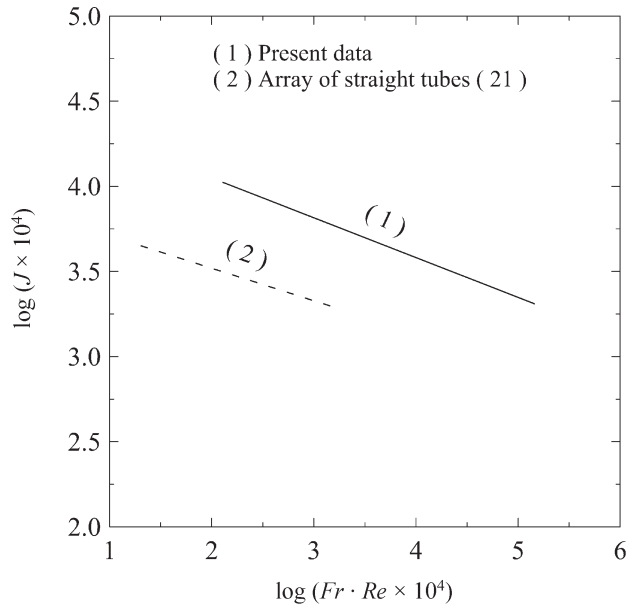


Fig. 7 - Comparison between the present mass transfer data and the data obtained for array of straight horizontal tubes

The high degree of axial dispersion reduces the driving force with a consequent decrease in the rate of mass transfer. Also, it is probable that, the flow conditions with helical coils are dominated by boundary layer separation effects and by wake interactions to large extent, compared with that which occurs with array of straight tubes, which in turn increase the mass transfer rate.

Conclusions

Mass transfer rates from helical coil geometry to gas-liquid systems were measured for a wide range of conditions. The dependence of the solid-liquid mass transfer coefficient on superficial gas velocity, the number of active rings per coil, and the physical properties of the liquid, was established.

It was shown that increasing the number of active rings per coil decreases the solid-liquid mass transfer coefficient. Increasing the superficial gas velocity was found to increase the mass transfer co-

efficient. The data were correlated using a dimensionless equation. This equation can be used to design and operate bubble columns and gas-sparged reactors that use helical coils as a catalyst supporting surface and heat exchanger. The present study has shown that helical coils are more efficient as transfer surface than arrays of straight tubes

Nomenclature

- C – constants
 a – active surface area, cm^2
 c – chromate mass concentration at time t , mol dm^{-3}
 c_0 – initial chromate mass concentration, mol dm^{-3}
 d_t – coil tube diameter, cm
 D – chromate diffusivity, $\text{cm}^2 \text{s}^{-1}$
 g – acceleration due to gravity, cm s^{-2}
 l_w – working section length, cm
 k – mass transfer coefficient, cm s^{-1}
 Q – solution volume, cm^3
 t – time, s
 v – superficial gas velocity, cm s^{-1}

Dimensionless groups

- Fr – froude number, $v^2/g d_t$
 J – mass transfer factor, $St \cdot Sc^{2/3}$
 Re – reynolds number, $\rho v d_t/\mu$
 Sc – schmidt number, $\mu/\rho D$
 St – stanton number, k/v

Greek symbols

- μ – solution viscosity, $\text{g cm}^{-1} \text{s}^{-1}$
 ρ – solution density, g cm^{-3}

References

1. Weissman, M. H., Mockeros, L. F., ASCE proc. Engng. Mech. Div. J., **94** (1968) 857.
2. David, A. N., The effect of secondary fluid motion on laminar flow heat transfer in helically coiled tubes. Sc. D thesis, mass. Inst. Technol., Cambridge, Mass. (1969).
3. Srinivasan, S., Chitien, Desalination **9** (1971) 127.
4. Kalb, C. E., Seader, J. D., AIChE. J., **20** (1974) 340.
5. Akiyama, M., Cheng, K. C., Int. J., Heat Mass Transfer **14** (1971) 1659.
6. Akiyama, M., Cheng, K. C., Int. J., Heat Mass Transfer **15** (1972) 1426.
7. Kalb, C. E., Seader, J. D., Int J., Heat Mass Transfer **15** (1972) 801
8. Austin, L R., Seader, J. D., AIChE. J., **19** (1973) 85.
9. Mujawar, B. A., Rao, M. R., Ind. Engng. Chem. **17** (1978) 22.
10. Morgan, V. T., Advances in Heat Transfer, Vol. 11, 244. Academic press, New York (1975).
11. Smith, A. F. J., Wragg, A. A., J. Appl. Electrochem. **4** (1974) 219.
12. Madden, A. J., Nelson, D. G., AIChE. J. **10** (1964) 415.
13. Vogel, A. I., A Text Book of Quantitive Inorganic Analysis, Longmans, London (1961).
14. Findly, A. Kitchener, A. J., Practical Physical Chemistry, 8th Edn., Longmans, London (1965).
15. Gregory, D. P., Riddiford, A. C., J., Electrochem. Soc., **107** (1960) 950.
16. Deckwer, W. D., Chem. Eng. Sci., **35** (1980) 1341.
17. Kast, W., Chem. Ing. Tech., **35** (1963) 785.
18. Upadhyay, S. N., Agrawal K. K. D., Sing, D. R., J., Chem. Japan **8** (1975) 413.
19. Cavatorta, O. N., Bohm, U., Chem. Eng. Res. Des., **66** (1988) 265.
20. Lewis, D. A., Field, R. W., Xavier, A. M., Edwards, D., Trans. IChemE., **60** (1982) 40.
21. Nosier, S. A., Chem. Eng. And Tech. **26** (2003) 1151.
22. Sultan, E., Nosier, S. A., Salem, A. Y., Mansour, I. S., Sedahmed, G. H., Chem. Eng. J., **91** (2003) 33.

