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Mass transfer at the confining wall of helically coiled circular tubes with gas–liquid flow and fluidized beds

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ABSTRACT

Experiments were conducted to investigate the effect of various dynamic and geometric parameters on mass transfer coefficients in two-phase helically coiled flow systems. Computation of mass transfer coefficients was facilitated by the measurement of limiting current at the electrodes fixed flush with the inner surface of the tube wall. Two flow systems were chosen: a two-phase liquid solid fluidized bed and a two-phase gas–liquid up flow. An equimolar potassium ferrocyanide and potassium ferricyanide solution in the presence of sodium hydroxide was used as the liquid phase. In the fluidized bed, glass spheres and sand of different sizes were employed as fluidizing solids. In two-phase flow system nitrogen was employed as inert gas. The pressure drop in the presence of fluidizing solids in helical coils was found to increase with increase in the pitch of the coil and was maximum for straight tube. The mass transfer coefficients were found to increase with increase in liquid velocity. The mass transfer coefficients in case of gas–liquid flow were found to be independent of liquid velocity and the pitch of the coil, and were largely influenced by gas velocity only. The data were correlated using j_D factor, Helical number, Froude number and Stanton number.

1. Introduction

Helically coiled tubes are commonly encountered and frequently employed in process industries. Advantages include simplicity, compactness, small residence times, low pressure loss, and high heat and mass transfer rates. Hence they find wide applications in chemical industries, petroleum industries, food industries and pharmaceuticals. When a fluid flows through a curved pipe, the curvature of the flow path generates the centrifugal force which acts at right angles to the main flow and results in secondary flows. The secondary flows thus generated led to increased turbulence and hence enhanced heat and mass transfer coefficients. Therefore, the coiled tube can be conceived as a passive augmentative device also. Flow through curved tubes are found in human body blood flow systems and industrial piping network. In chemical and allied industries, the helically coiled tubes are used in compact heat exchangers, coil steam generators, boilers, evaporators, reverse osmosis units, nuclear reactors, fluid mixing units, waste heat recovery units, power production units, cooling systems of electric generators, exhaust gas ducts of engines, thermosyphones etc. An important application is as phase separators in petroleum industries. In two-phase flow, when the flow enters the curved portion, the heavier density phase is subjected to a larger centrifugal force and this force causes the liquid to move away from the centre of the curvature. This process is a continuous function of coil geometry. The curved pipe separator is an innovative device which proved to be cost effective compared to the conventional sedimentation tank and hydro cyclone. This has many important applications in petroleum industry. Oil–gas two-phase flow and oil–gas–water three-phase flow are handled in helically coiled tube heat exchangers. Sand is often carried from oil wells in addition to oil–water emulsions and natural gas streams. Decanting is essential because the coexistence of sand and oil would cause serious wearing and clogging problems to the operational facilities and equipment. Also, gas–solid two-phase flow occurs in the bends of pneumatic conveying pipelines.

Electrochemical reactors are widely used in many industrial processes such as metal extraction, electrodeposition, electroplating and electrowinning. Knowledge of the liquid–wall mass transfer data is essential in the design of such reactors. An understanding of the behavior of liquid–wall mass transfer coefficient is also needed to derive analogy between heat and mass transfer. Hofmann and Halász [1] investigated the radial mass transport in ideal and helical coiled tubes with circular cross-section. The advantage of using these coiled tubes in liquid chromatography for rapid radial mass transfer has been discussed. Potential applications as heat exchangers, mixing tubes, reaction detectors, connecting tubing among sampling device, column and detector in high performance liquid chromatography (HPLC) have been described.

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Nomenclature

A	surface area of electrode (m^2)
A_t	cross-sectional area of the tube (m^2)
C_0	bulk concentration of reacting species ($kmol/m^3$)
d	diameter of tube (m)
D	diameter of coil (m)
D_L	diffusivity of reacting ion (m/s^2)
F	Faraday constant, 96,500 (C/equivalent)
Fr_P	Froude number based on particle diameter, U_L^2/gd_P
Fr_g	Froude number based on gas velocity, U_g^2/gd
He	Helical number, $Re[(d/D)/(1+(p/\pi D)^2)]$
i_L	limiting current (A)
j_D	Coulburn factor, $(k_L/U_L)Sc^{2/3}$
k_L	mass transfer coefficient (m/s)
L	length of coil (m)
n	number of electrons released (or) consumed during the reaction
p	pitch (m)
Re_L	Reynolds number based on liquid velocity, $\rho dU_L/\mu$
Sc	Schmidt number, $\mu/\rho D_L$
St_g	Stanton number based on gas velocity, k_L/U_g
U_g	gas velocity (m/s)
U_L	liquid velocity (m/s)
W_S	weight of the solids (kg)

Greek symbols

ε	void fraction
μ	viscosity of liquid (kg/(m s))
ρ_S	density of solids (kg/m^3)

Table 1
Range of variables covered.

Parameter	Value(s)/range
Liquid velocity	0.0072–1.6966 m/s
Gas velocity	0–0.5 m/s
Tube diameter	1.8 and 2.3 cm
Tube pitch	0.5, 1.0, 2.0, 2.5, 3.0 and 5.0
Tube length	1.56, 2.8 and 3.1 m
Coil diameter	20 cm
Diameter of glass balls	3.13 mm
Size of sand particles	0.5 and 1.0 mm

A comprehensive review of pressure drop studies for flow through helical coils has been made by Ali [2]. In addition to summarizing the available correlations for pressure drop, Ali [2] also conducted experiments to verify these correlations and presented a more generalized correlation. Austin and Seader [3] obtained solutions of the equations of fluid motion for the case of steady state, fully developed, isothermal, incompressible, viscous Newtonian flow with a toroidal type coiled tube geometry. The objective of this study was to develop a rapidly converging and reasonably accurate numerical solution for equations of fluid motion. Fully developed pulsatile flow in a curved tube has been investigated by Hamakiotes and Berger [4]. Mathematical formulation of the flow situation was made so that the governing equations were solved numerically. The experimental and theoretical results were compared. The influence of curvature on the laminar to turbulent flow transition was reported from direct inspections of the experimental friction factor profiles by Cioncolini and Santini [5].

Heat transfer enhancement was facilitated in coiled tube heat exchangers without undue increase in pressure drop. Acharya et al. [6] analyzed the phenomenon of steady heat transfer augmentation due to chaotic particle paths in steady, laminar flow through a coiled tube. Prabhanjan et al. [7] predicted the outlet temperature of the fluid flowing through the helically coiled tube using a model which has been developed.

Experimental investigation and comparative study were carried out by Xin et al. [8] on the pressure drop with air–water two-phase flow in vertical helicoidal pipes. The geometrical parameters such as helix angle, coil diameter and pipe diameter were found to affect the frictional pressure drop. The internal structure of air–water two-phase flow in a helically coiled tube was experimentally investigated by Murai et al. [9]. Three types of flow regimes viz., bubbly flow, plug flow and slug flow were observed and flow regime maps were plotted. An experimental and numerical study of two-phase flow in helically coiled tube was carried out by Gao et al. [10]. Phase separations and particle concentration peaks and the effects of different forces on these have been investigated. Effect of particle size, liquid flow rate and coil curvature on two-phase flow was also examined. Mandal and Das [11] carried out experimental investigations to study the two-phase pressure drop and hold up for flow through helical coils. The helix angle was varied from 0° to 12°. It was reported that the helix angle had not shown any effect on two-phase pressure drop and hold up.

Gas–liquid mass transfer into falling liquid film in helically coiled tubes had been investigated by Hameed and Muhammed [12]. The absorption of carbon dioxide into liquid films of distilled water, 96.25% ethanol and ethylene glycol of 12% or 5.2% was carried out. The gas–liquid mass transfer coefficient was found to have higher values in coiled tubes compared to straight tubes. It was further reported that change of helical tube pitch by 3–5° had no influence on mass transfer coefficient.

Most of the reported studies in coiled flow were aimed at estimating pressure drop and friction factor and on using helically coiled tubes as heat exchangers. However, studies on using helically coiled tubes for mass transfer are sparse [13]. Hence an attempt is made to investigate the effect of various dynamic and geometric variables on wall–liquid mass transfer in two-phase flow systems viz., gas–liquid and solid–liquid in helically coiled tubes. The liquid phase chosen was an electrolyte of ferri–ferrocyanide solution. In gas–liquid flow, the gas used was inert nitrogen gas. In solid–liquid fluidized bed, sand particles of different sizes were employed as bed material. Measurement of mass transfer coefficient is made using the limiting current technique. The ranges of experimental variables covered are presented in Table 1.

2. Experimental

The equipment was designed and fabricated to carry out studies on mass transfer at the inner surface of a helically coiled circular tube. The schematic of the experimental setup used in the present investigation was provided in Fig. 1. The equipment consisted of a cylindrical storage tank (S), centrifugal pump (P) for circulating the fluid electrolyte, two rotameters (R_1 and R_2) for measuring the flow rate of the electrolyte, and U-tube manometer (U) to measure the pressure difference across the helical coil. Valves (V_1–V_5) were used to control the flow rate of the liquid. Nitrogen was used as the inert gas phase. Valves V_6 and V_7 were used to control the flow rate of nitrogen gas from the cylinder (N). A wet gas meter (G) was used to measure the flow rate of the nitrogen gas. The exact measurement of gas flow rate was facilitated by employing two open-end manometers (M_1 and M_2).

The storage tank was completely covered with an ebonite sheet in order to eliminate continuous contact with the atmospheric air. A spiral coil (SC) with perforations was placed in the storage tank for deaeration of the electrolyte with nitrogen gas. The helical coils were made using transparent thick-walled polythene tubing of 1.8 cm and 2.3 cm internal diameter with the coil diameter of

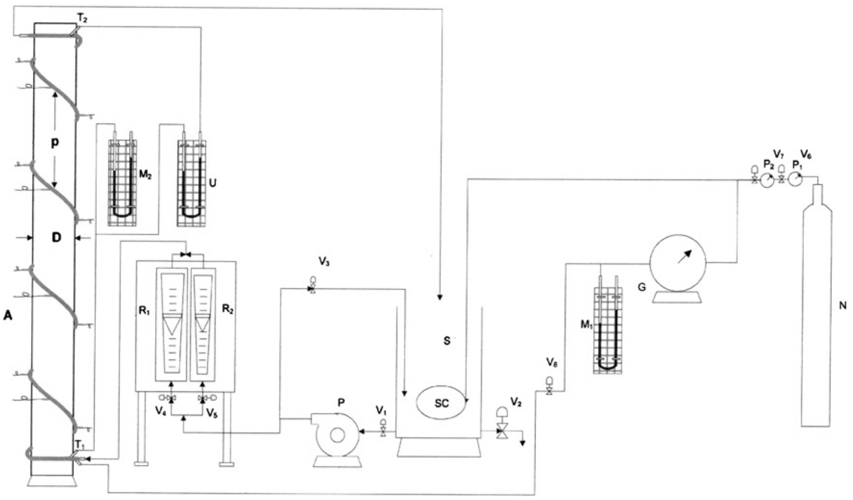

Fig. 1. Schematic of experimental unit. A, helical coil wound on a pipe; G, wet gas meter; M_1 and M_2, open end manometers; N, nitrogen gas cylinder; P, pump; P_1 and P_2, pressure gages; R_1 and R_2, rotameters; S, storage tank; SC, spiral coil; T_1 and T_2, pressure taps; U, manometer; V_1–V_8; valves.

20.0 cm. The inner walls of these coils were provided with nickel point electrodes of 3.42 mm diameter. One end of these electrodes was fixed flush with the surface of the inner wall of the coil while the other end projected outward served as terminal for connecting the electrodes to the external circuit. Two pressure taps (T_1 and T_2) at the beginning and end of the coil were provided to measure pressure drop across the coil. These taps were connected to the limbs of a U-tube manometer to measure the pressure drop.

Prior to the assembly of the coiled tubular electrochemical reactor, the surfaces of the point electrodes were polished and cleaned thoroughly. An equimolar solution of potassium ferrocyanide and potassium ferricyanide of 0.01N in the presence of 0.5N sodium hydroxide was used as the electrolyte. The electrode reaction involved in this study was reduction of ferricyanide ion:

$$[\mathrm{Fe(CN)_6}]^{3-} + \mathrm{e} \rightarrow [\mathrm{Fe(CN)_6}]^{4-} \tag{1}$$

From the measured limiting current data at any given electrode of area A, the mass transfer coefficients were evaluated [14] using the equation:

$$k_L = \frac{i_L}{nAFC_0} \tag{2}$$

where C_0 is the concentration of reacting ion in the bulk electrolyte. The bed porosity ε was obtained as

$$\varepsilon = 1 - \frac{W_S}{\rho_S A_t L} \tag{3}$$

3. Results and discussion

Initially pressure drop data were obtained in empty coils. These data were found to be in good agreement with the equation proposed by Mishra and Gupta [15]. In conducting experiments with fluidizing solids, a wire mesh was used to support the bed of solids. The wire mesh also served as a sparger when two-phase gas–liquid flow was employed. Mass transfer coefficient data were obtained from the measured limiting current data for various flow systems and were compared by plotting them against Reynolds number based on liquid velocity in Fig. 2. Plot A in Fig. 2 represents the data predicted from Lin et al. [14] for the case of flow through straight tube. Plot B shows the mass transfer coefficient data of Harvind Kumar [16] obtained in a helically coiled tube with homogeneous flow of electrolyte with a p/D ratio of 2.5. The augmentation in case of helically coiled tube in comparison with straight tube (Plots B and A) was up to 235% at lower Re_L end and up to 135% at higher Re_L end. The present experimental data on mass transfer coefficient, k_L, obtained with 1 mm sand particles as fluidizing solids have been plotted against Re_L with $p/D = 2.5$ and were shown in Plot C. An improvement of 10% in mass transfer coefficient was realized by employing fluidizing solids over empty coil (Plots C

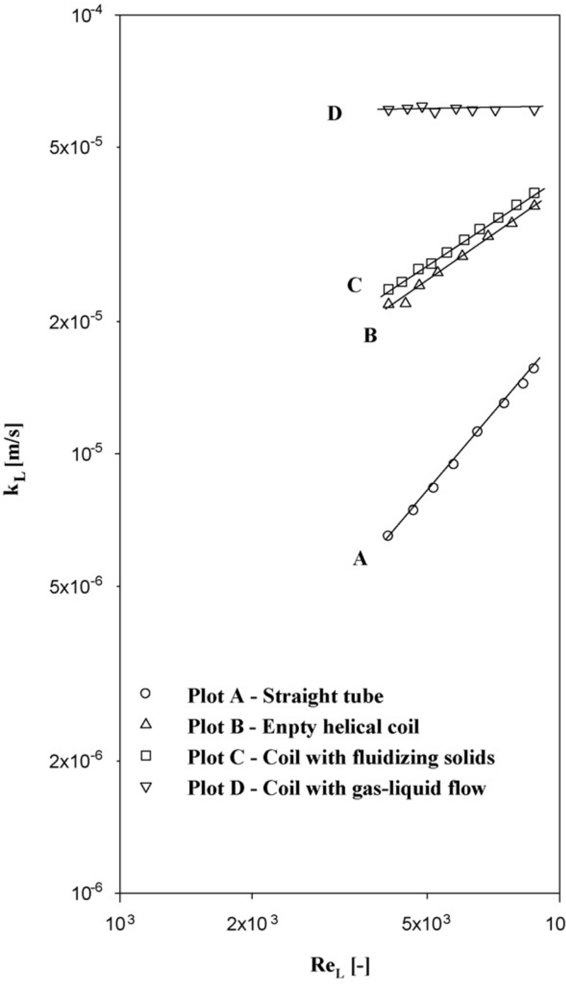

Fig. 2. Augmentation of mass transfer coefficient in helically coiled tube with $p/D = 2.5$ in comparison with straight tube data.

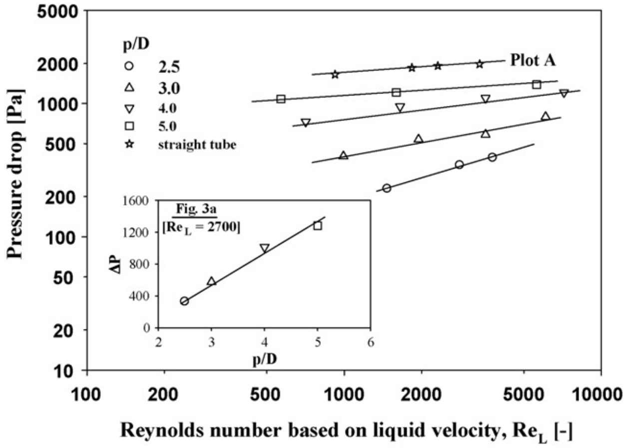

Fig. 3. Variation of pressure drop with Reynolds number based on liquid velocity.

and B). The present experimental data obtained with two-phase gas–liquid flow system when the nitrogen gas velocity was constant at 0.5 m/s was shown in Plot D. It can be noticed that the mass transfer coefficients obtained in two-phase gas–liquid flow systems were 10 times higher than empty straight tube mass transfer coefficient data (Plots D and A) and up to 2.8 times with respect to mass transfer coefficient data in empty helical coil (Plots D and B). The flow through helical coils can thus be viewed as a passive augmentative device and magnitudes of improvement in mass transfer coefficients are assured. Therefore an attempt is made to carry out a systematic investigation of the effect of various pertinent dynamic and geometric variables on mass transfer in helical coiled circular tubes with a bed of fluidizing solids and also two-phase gas–liquid flow.

3.1. Studies in helically coiled circular tubes in the presence of fluidizing solids

When the p/D ratio was less than 2.5, the solids were found to simply move or slip along the wall of the tube. The solids bed was fluidized only when the p/D ratio was equal to or more than 2.5 at which the centrifugal force on the solid particle besides drag, gravitational and buoyancy forces might have prevailed to keep the solids bed in the coiled tube under fluidized condition.

3.1.1. Effect of pitch on pressure drop

Pressure drop in a fluidized bed is essentially due to bed weight. Since weight expressed as force being a vector quantity, the vertical component of the weight in the coiled tube would be less in comparison with that of a straight tube. Hence the pressure drop across the fluidized bed will increase with increase in pitch and reach a maximum for infinite pitch i.e., straight tube. In the present study, pressure drop data were obtained for various p/D ratios viz., 2.5, 3, 4, 5 and $\propto$. The data obtained with glass balls of 3.13 mm diameter were plotted against Reynolds number based on liquid velocity and shown in Fig. 3. It was observed that the pressure drop increased with increasing Reynolds number for all p/D ratios of the present investigation. Also it is conspicuous from the inset of Fig. 3 that the pressure drop increased with increasing p/D ratio and pressure drop in straight tube was found to be maximum (plot A).

3.1.2. Effect of particle size on mass transfer coefficient

It is well known that the fluid film present on the reacting surface offers resistance to mass transfer. Reduction in the thickness of this fluid film leads to enhanced mass transfer rates. Presence of solid particles results in scouring action which considerably decreases the film thickness. The larger particles are likely to cause more intense scouring action, resulting in a significant reduction in film thickness, yielding higher mass transfer coefficients. Jagannadha Raju and Rao [17] in their studies on wall-to-bed mass transfer in fluidized beds observed that the mass transfer coefficient at the electrode surface increased with increase in particle diameter. Similar observations were also made by Ramesh et al. [18,19] in three-phase fluidized beds. To investigate the effect of particle diameter on k_L in the coiled flow, data were obtained with sand of two different sizes of 0.5 and 1.0 mm as bed material. Fig. 4 shows the present experimental data on mass transfer coefficient plotted against Reynolds number based on liquid velocity, obtained with sand of 0.5 and 1.0 mm size particles with $p/D = 3.0$. The mass transfer coefficient was found to increase with increasing liquid velocity. The plots of the data showed that particles of 1.0 mm size yielded higher coefficients at any liquid velocity.

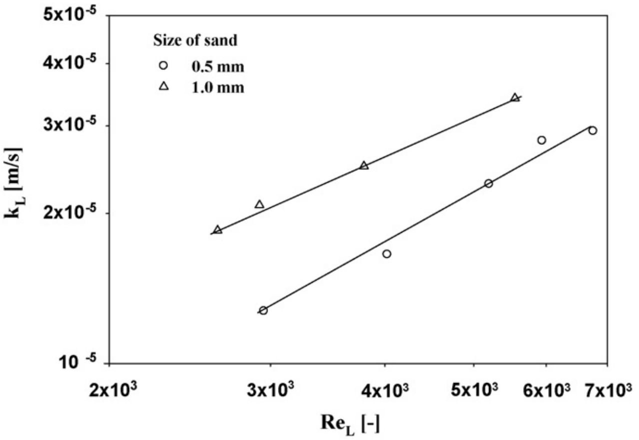

Fig. 4. Effect of particle diameter: variation of mass transfer coefficient with Reynolds number based on liquid velocity for $p/D = 3.0$ with sand particles.

3.1.3. Effect of pitch on mass transfer coefficient

For lower values of p/D ratio, the centrifugal force action along the curved path can be expected to be more due to large curvature of the flow path. Thus the particles strike the wall of the coil vigorously reducing the thickness of fluid film at the electrode surface that results in higher mass transfer coefficients. As the p/D ratio is increased, the mass transfer coefficients were found to be low as expected due to weakening of centrifugal action along the flow

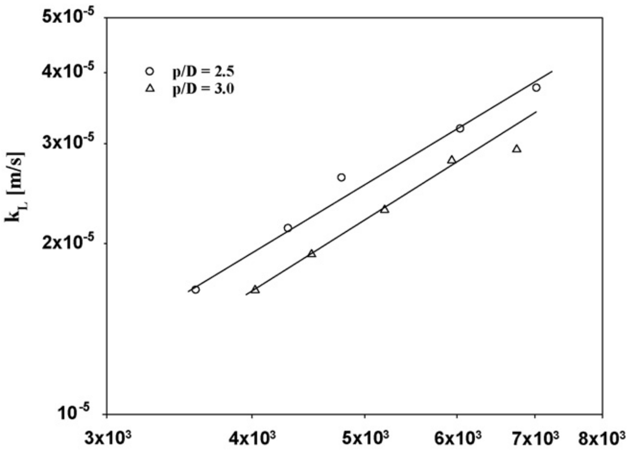

Fig. 5. Effect of pitch of the coil: variation of mass transfer coefficient with Reynolds number based on liquid velocity with 0.5 mm sand particles.

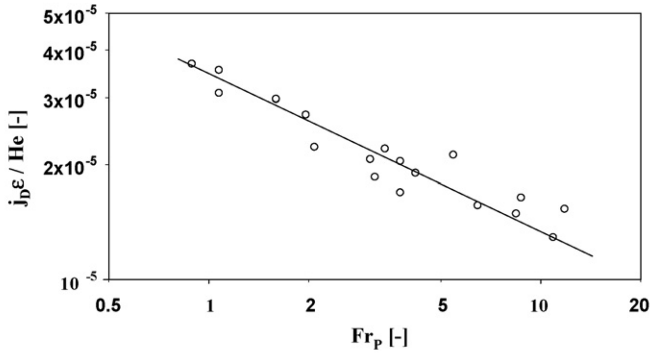

Fig. 6. Correlation plot in case of helical coils with fluidizing solids.

path. The data on k_L were plotted against Re_L and shown in Fig. 5 for p/D ratios of 2.5 and 3 for the case of sand of 0.5 mm size as bed material. The plots revealed marginal variation of mass transfer coefficient with p/D ratio. However, mass transfer coefficient data at higher p/D ratios are required to establish the effect of pitch on mass transfer coefficient.

3.1.4. Correlation

The entire data on mass transfer coefficients in fluidized beds are correlated using j_D factor. To account for the curvature of the coiled configuration, Helical number is incorporated and resulting correlation on regression analysis is as follows:

$$j_D\varepsilon = 3.2 \times 10^{-5}(He)(Fr_P)^{-0.38} \qquad (4)$$

Average deviation = 11.07%; standard deviation = 13.46%.

The experimental data in accordance with Eq. (4) were plotted and shown in Fig. 6. The calculated j_D data were compared with the experimental j_D data and shown in Fig. 7. The data were found to agree within a maximum error margin of ±20%.

3.2. Studies in helically coiled circular tubes with two-phase gas–liquid flow

Studies on wall–liquid mass transfer in gas–liquid two-phase up flow were reported by Yasunishi et al. [20]. Introduction of even small amounts of gas into homogeneous liquid flow is very significant in enhancing the mass transfer coefficient. It was observed that presence of gas phase in two-phase flow, even masked the effect of liquid velocity on mass transfer coefficients. This increase in mass transfer coefficient is due to the increased turbulence in the liquid phase by the agitating gas bubbles. An attempt is made to investigate the effect of two-phase flow through helically coiled circular tubes on the augmentation of wall–liquid mass transfer coefficient.

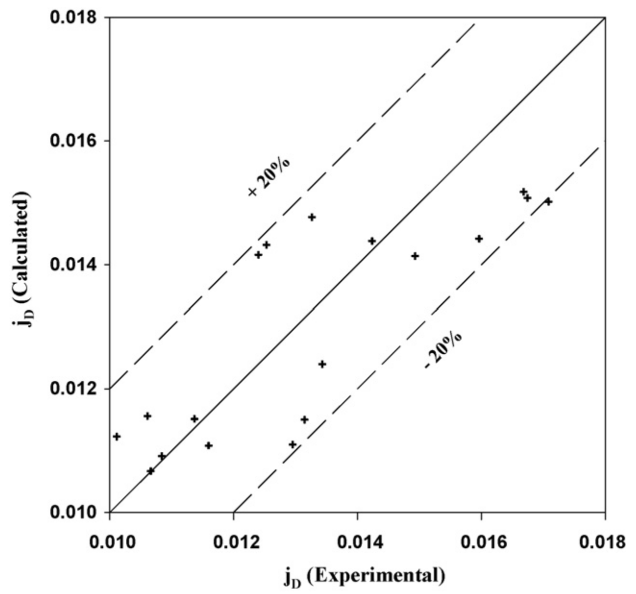

Fig. 7. Comparison of experimental and calculated j_D data from Eq. (4).

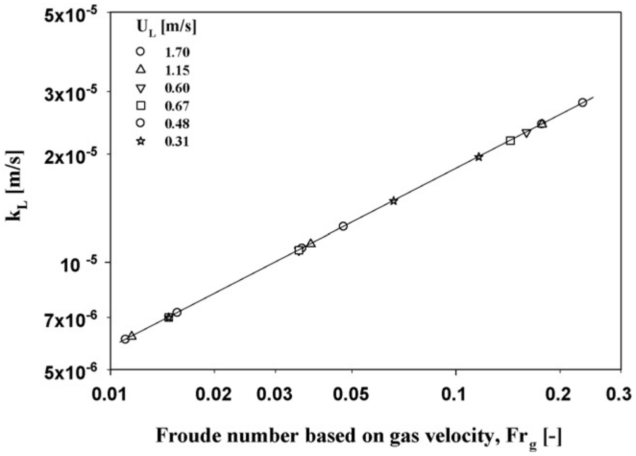

Fig. 8. Variation of mass transfer coefficient with Froude number based on gas velocity at various liquid velocities for $p/D = 0.5$.

3.2.1. Effect of gas and liquid velocities on mass transfer coefficient

In two-phase gas–liquid flow [20], the velocity of gas exhibits strong influence on wall–liquid mass transfer. Yasunishi et al. [20] observed that the wall–liquid mass transfer coefficient was largely influenced by gas velocity and relatively independent of liquid velocity in gas–liquid up flow bubble columns. Ramesh et al. [18,19] reported that the effect of liquid velocity on wall-to-bed mass transfer coefficient was insignificant in three-phase fluidized beds when the liquid velocity was varied over a moderate range. With these observations, one can anticipate that even in the helical coils the effect of liquid velocity would be marginal on wall–liquid mass transfer coefficient in case of two-phase flow. The present experimental data on k_L were plotted against Froude number based on gas velocity, Fr_g obtained for constant liquid velocities for the case of helical coiled tubes with a p/D ratio of 0.5 and shown in Fig. 8. The plot of the figure showed that the mass transfer coefficient increased with increase in Fr_g and was independent of liquid velocity. The ranges of gas and liquid velocities employed in the present investigation resulted in either bubbly flow regime or plug flow regime as reported earlier by Murai et al. [9].

3.2.2. Effect of pitch on mass transfer coefficient

Augmentation in mass transfer coefficient can be achieved by increased turbulence which reduces the thickness of the resistance film on the reacting surface effectively. The turbulence generated in helically coiled tubes with gas–liquid flow can be attributed to: (1) secondary flows resulting from centrifugal force due to coil curvature and (2) vigorous agitation caused by the flow of gas. To study the effect of pitch on k_L, experimental data for different p/D ratios and for comparison, the data with straight pipe were obtained. Fig. 9 gives the data on k_L plotted against Fr_g for different p/D ratios. Fig. 9a is the cross-plot of the data of Fig. 9 showing the effect of p/D ratio on k_L. Mass transfer coefficient was found to be independent of p/D ratio. Hameed and Muhammed [12] while investigating the gas–liquid mass transfer in helically coiled tubes observed that pitch of the coil showed no effect on gas–liquid mass transfer coef-

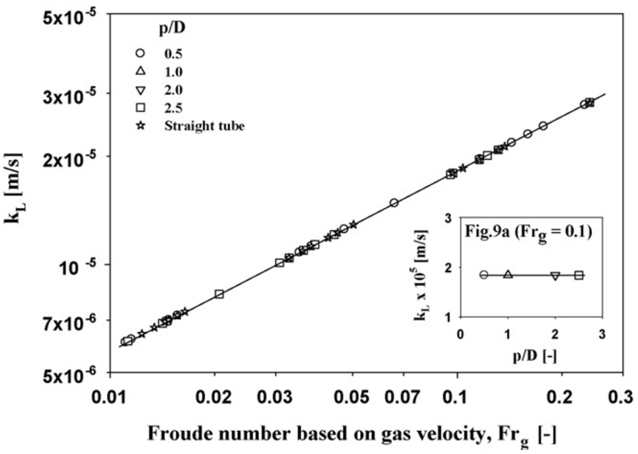

Fig. 9. Effect of pitch: variation of mass transfer coefficient with Froude number based on gas velocity at a constant liquid velocity of 1.15 m/s.

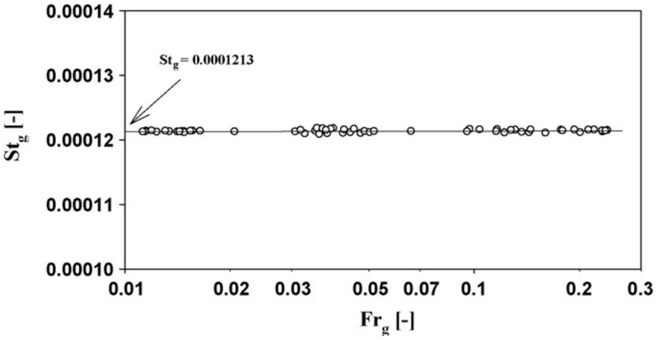

Fig. 10. Correlation plot for the case of helical coil with gas–liquid flow.

ficient when pitch expressed as helix angle, was varied up to 3–5°. Mandal and Das [11] during their investigation on pressure drop and hold up in two-phase flow in helical coils also reported that the pitch had not shown any effect on pressure drop and hold up when the pitch was varied between 0° and 12°. These observations revealed that the helically coiled tubes offered no substantial advantage over straight tubes in augmenting the wall–liquid mass transfer coefficient in gas–liquid flow systems. However, the advantage of the compactness of helically coiled tubes over straight tubes cannot be undermined as such systems find wide usage in process as well as in space engineering applications.

3.2.3. Correlation

The mass transfer coefficient k_L was found to be independent of liquid velocity and p/D ratio and was affected by gas velocity only. The data on mass transfer coefficient were therefore correlated as a function of gas velocity using Stanton number based on gas velocity as:

$$St_g = \frac{k_L}{U_g} = 1.213 \times 10^{-4} \qquad (5)$$

Excellent fit of the data in accordance with Eq. (5) shown in Fig. 10 was found with a marginal deviation of less than 1%.

4. Conclusions

The pressure drop in fluidized helical coils increased with increase in p/D ratio. Improvements in mass transfer coefficient in helical coils in the presence of fluidizing solids were 10% more than those with homogeneous flow in the same coil while the improvements were found to be 2.5 times more than those with straight tube. The mass transfer coefficient increased with increasing liquid velocity and particle diameter in case of helically coiled fluidized beds. The mass transfer coefficient was found to be independent of liquid velocity and p/D ratio but was strongly affected by gas velocity in two-phase gas–liquid up flow systems.

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References

[1] K. Hofmann, I. Halász, Mass transfer in ideal and geometrically deformed open tubes, J. Chromatogr. 173 (1979) 211–228.
[2] S. Ali, Pressure drop correlations for flow through regular helical coil tubes, Fluid Dynamics Res. 28 (2001) 295–310.
[3] L.R. Austin, J.D. Seader, Fully developed viscous flow in coil tubes, AIChE J. 19 (1973) 85–94.
[4] C.C. Hamakiotes, S.A. Berger, Fully developed pulsatile flow in a curved pipe, J. Fluid Mech. 20 (1988) 23–55.
[5] A. Cioncolini, L. Santini, An experimental investigation regarding the laminar to turbulent flow transition in helically coiled pipes, Exp. Thermal Fluid Sci. 30 (2006) 367–380.
[6] N. Acharya, M. Sen, H.-C. Chang, Analysis of heat transfer enhancement in coiled tube heat exchangers, Int. J. Heat Mass Transfer 44 (2001) 3189–3199.
[7] D.G. Prabhanjan, T.J. Rennie, G.S. Vijaya Ragavan, Natural convection heat transfer from helical coiled tubes, Int. J. Thermal Sci. 43 (2004) 359–365.
[8] R.C. Xin, A. Awwad, Z.F. Dong, M.A. Ebadian, H.M. Soliman, An investigation and comparative study of the pressure drop in air–water two-phase flow in vertical pipes, Int. J. Heat Mass Transfer 39 (1996) 735–743.
[9] Y. Murai, S. Yoshikawa, S. Joda, M. Ishikawa, F. Yamomoto, Structure of air–water two-phase flow in helically coiled tubes, Nuclear Eng. Design 236 (2006) 94–106.
[10] H. Gao, L. Guo, Z. Zhan, Liquid–solid separation phenomena of two-phase turbulent flow in curved pipes, Int. J. Heat Mass Transfer 45 (2002) 4995–5005.
[11] S.N. Mandal, S.K. Das, Gas–liquid flow through coils, Korean J. Chem. Eng. 20 (2003) 624–630.
[12] M.S. Hameed, M.S. Muhammed, Mass transfer into liquid falling film in straight and helically coiled tubes, Int. J. Heat Mass Transfer 46 (2003) 1715–1724.
[13] T. Anil Kumar, Mass transfer at the confining wall of helically coiled circular tubes with gas–liquid flow and fluidized beds, M. Tech. dissertation, Andhra University, Visakhapatnam, India (2008).
[14] C.S. Lin, E.B. Denton, H.S. Gaskill, C.L. Putan, Diffusion-controlled electrode reactions, Ind. Eng. Chem. 43 (1951) 2136–2143.
[15] P. Mishra, S.N. Gupta, Momentum transfer in curved pipes. 1. Newtonial fluids; 2. Non-Newtonial fluids, Ind. Eng. Chem. Process Des. Dev. 18 (1979) 130–142.
[16] R. Harvind Kumar, Mass transfer at the confining wall of helically coiled circular tubes in the absence and presence of packed solids, M. Tech. dissertation, Andhra University, Visakhapatnam (2008).
[17] G.J.V. Jagannadha Raju, C.V. Rao, Ionic mass transfer in the presence of fluidizing solids, Indian J. Technol. 3 (1967) 201–205.
[18] K.V. Ramesh, G.M.J. Raju, C. Bhaskara Sarma, R.V. Subba Raju, Liquid–wall mass transfer in three-phase fluidized beds with cross-flow of electrolyte, Chem. Eng. J. 135 (2008) 224–231.
[19] K.V. Ramesh, G.M.J. Raju, C.B. Sarma, Ch.V.R. Murthy, R.V.S. Raju, Liquid–wall mass transfer in three-phase fluidized beds with annular flow, Indian Chem. Eng. 50 (2008) 277–287.
[20] A. Yasunishi, M. Fukuma, K. Muroyama, Wall to liquid mass transfer in packed and fluidized beds with gas–liquid concurrent up flow, J. Chem. Eng. Jpn. 21 (1988) 522–528.