HEAT TRANSFER IN BUBBLE COLUMN CONTACTORS WITH IMMERSED COILED HEATER

Majid Ibrahim Abdul-Wahab
Chemical Engineering Department – College of Engineering - University of Baghdad - Iraq

Abstract

Heat transfer coefficient has been measured in gas-liquid dispersions (water-air system). Experiments were performed over a range of liquid and gas flow rates in a 0.22 m diameter column fitted with an axially mounted coiled heater. The experimental results were compared with the previously published heat transfer correlations and the agreement is very satisfactory. A new correlation for the heat transfer coefficient in bubble columns fitted with immersed coil was developed and applied to the theoretically derived equation of Deckwer (1980) which combine the surface renewal theory of mass transfer with Kolmogoroff's theory of isotropic turbulence [2]. The application of the present data to the Deckwer model gave a very good agreement.

Introduction

There are many processes in chemical industries, which are carried out by contacting gas bubbles with a liquid phase. The chlorination of liquid benzene and other hydrocarbons with gaseous chlorine is an example of gas-liquid reactions. In the inorganic field we have the manufacture of sodium amide, from gaseous ammonia and liquid sodium. The gas-liquid reactions may also take place in the removal of an undesired impurities from a gas, thus the absorption of a solute gas by a liquid may be accelerated by adding a suitable material to a solvent which will react with the solute being absorbed. A further important points of the wide use of gas-liquid reactors results from the favorable heat transfer properties of gas-liquid dispersions. As a rule of thumb one can say that in gas-liquid dispersions the heat transfer coefficients are larger by a factor of 100 than in one phase flow. Sattefield [1] pointed out that this fact is one of the major reasons for the application of such systems in the most highly exothermic reactions.

The residence time distribution and the temperature are the main factors governing the selectivity of complex reactions. In the gas-liquid contactors, the temperature is practically constant over the whole reactor volume due to the high heat capacity of the liquid phase and the large dispersion prevailing in such contactors, therefore, the temperature of the reactor can be controlled easily by providing sufficient heat transfer area. It is therefore obvious that application of gas-liquid reactors is practically recommended if temperature sensitive process are to be performed.

The most widely used of gas-liquid contactors are the well-stirred tank and bubble column reactors. Beside their cheap and simple construction, bubble columns are frequently superior over stirred tanks particularly at higher temperatures and pressures where shaft sealing may be difficult [2].

Many attempts were made to correlate the rate of heat transfer from a surface immersed in a bubbly liquid [2, 3, 4]. Because of the large number of variables, each investigator gave a correlation for the heat transfer rate that holds for a certain type of heating and for a limited range of operating conditions.

In this work, experiments were carried out in a bubble column heated by an immersed coiled heater, to investigate the heat transfer process and measure the heat transfer coefficient in such columns. The results compared with the previous published correlations, as well as with the theoretically derived equation of Deckwer [2] for the heat transfer in bubble columns, which combines the surface renewal model for mass transfer with Kolmogoroff's theory of isotropic turbulence.

Previous Work

Heat transfer from the wall of the column or from the immersed heating elements (rods or planes) to gas-liquid dispersions was studied by several investigators. A summary of this work was presented by Steiff and Weinspach [5] and more recently by Soria, et al.[6]. Kölbel et al.[7], show that the main factors affecting the results are the gas velocity and liquid phase properties. They found that the geometrical sizes of the columns used did not effect the heat transfer. They found also that the gas distributor design has no influence on the heat transfer rate data. They presented their results in the form:

$$Nu = c\,Re^{m} \qquad ......(1)$$

Which involve the characteristic length parameter.

Kast [8] analyzed the motion of fluid elements around a gas bubble rising in the column and recognized that the heat transfer coefficient was a function of radial velocity component of the liquid and the physical parameters. He derived:

$$h \propto u_r \rho C_p \qquad \ldots\ldots(2)$$

The radial velocity is assumed to be proportional to the superficial gas velocity. By using the Stanton number $St = h/u_g \rho C_p$ and with the results of Kölbel et al.[7], the following relation was proposed.

$$St = f(\mathrm{Re}\, Fr\, \mathrm{Pr}^2) \qquad \ldots\ldots(3)$$

Mersmann [9] established a diagram by means of which the heat transfer coefficient can be estimated. Many other workers obtained correlations for the calculation of the heat transfer coefficient in the bubble columns, these correlations can be seen in Table (1).

Table (1): Empirical correlations of heat transfer coefficients in bubble columns

Author	Correlation	Number
Kast, 1962	$St = 0.1(\mathrm{Re\,Fr\,Pr}^2)^{-0.22}$	4
Kölbel et al., 1958	$St = 0.124(\mathrm{Re\,Fr\,Pr}^{2.5})^{-0.22}$	5
Shaykhutdinov et al.,1971	$St = 0.11(\mathrm{Re\,Fr\,Pr}^{2.5})^{-0.22}$	6
Burkel, 1972	$St = 0.11(\mathrm{Re\,Fr\,Pr}^{2.48})^{-0.23}$	7
Hart, 1976	$St = 0.125(\mathrm{Re\,Fr\,Pr}^{2.4})^{-0.25}$	8
Steif, Weinspach, 1978	$St = 0.113(\mathrm{Re\,Fr\,Pr}^2)^{-0.26}$	9
Louisi, 1979	$St = 0.136(\mathrm{Re\,Fr\,Pr}^{1.94})^{-0.27}$	10

Deckwer [2] started from the view of Kast [8], he derived theoretically an equation for the heat transfer in bubble agitated systems. This derivation was done by combining the surface renewal model of mass transfer with Kolmogoroff's theory of isotropic turbulence. The derived equation was:

$$h \propto k^{0.5} \rho^{0.75} C_p^{0.5} \mu^{-0.25} g^{0.25} u_g^{0.25} \qquad \ldots\ldots(11)$$

Which can be rearranged to:

$$St = c\,(\mathrm{Re}\, Fr\, \mathrm{Pr}^2)^{-0.25} \qquad \ldots\ldots(12)$$

Equation (11) shows the correct dependency of the heat transfer coefficient on all six parameters which effect heat transfer, and describes available experimental data covering a range of $6 < \mathrm{Pr} < 1000$ with good agreement.

Experimental Work

The diagram of the apparatus used for the present investigation was shown in Fig.(1). It consists of cylindrical glass column, 1.5 m high, and 0.22 m internal diameter. Ring type gas distributor was used with diameter ratio of 0.6 with respect to column diameter. Gas flow rates were measured by calibrated rotameters, while liquid flow rates by calibrated orifice meter. A variac transformer supplied power. A 3-kW immersion-heating coil heated the column. The surface temperature of the coil was measured by two embedded thermocouples, and the bulk temperatures were calculated as the average of the readings of five thermocouples placed in different radial positions with an assembly which allows for the up and down axial movement.

Kim et al. [10], studied the heat transfer characteristics in coal slurry-gas system, and found that the heat transfer coefficient increased with gas flow rate and decreased with the viscosity of the slurry at a given slurry velocity. The heat transfer coefficient was found to be about three to five times that of a bed of liquid alone.

For a given gas flow rate and heater power input, the steady-state temperature differences between the thermocouples in the heater and the thermocouples in the liquid were recorded by a multi-channel temperature recorder. The fluctuation in temperature readings was overcome by taking the means of repeated measurements.

The heat transfer coefficient, h was calculated as:

$$h = \frac{Q}{A_s(T_w - T_B)} \qquad \ldots\ldots(13)$$

Where Q is the power input to the heater, A_s is the surface area of the heater, T_w and T_B are the wall and liquid bulk temperatures respectively.

The experimental conditions used for the system studied are given in Table (2).

Table (2): Experimental conditions for the system studied.

System	u_L range (m/s)	u_g range (m/s)	ρ_L kg/m^3	μ_L Ns/m^2	k_L W/m K	C_p J/kg K	T_B °C
Air-Water	0.011-0.05	0- 0.165	1000	$(0.38\text{-}1.3)\times10^{-3}$	0.59-0.66	4200	25-50

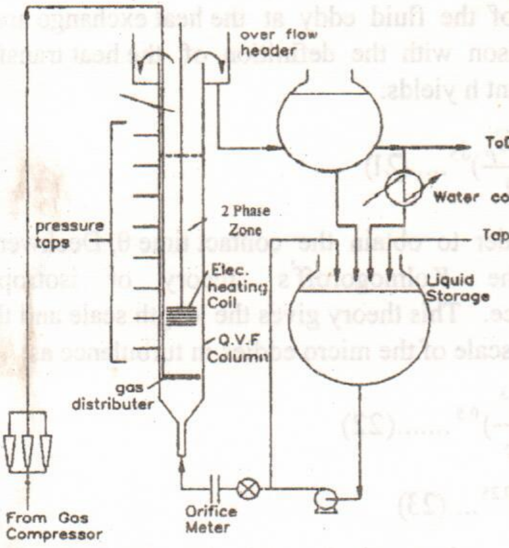

Fig. (1) Schematic Diagram of the Equipment

Results and Discussion

In this study, measurements of heat transfer coefficients were performed in gas-liquid dispersions. Some preliminary measurements of heat transfer coefficients were made with liquid alone flowing through the column. The values of these coefficients were found to be about double those predicted from Sieder-Tate equation [12, 13]. This is probably not unreasonable since the Sieder-Tate equation is valid only for fully developed turbulent flow inside tubes having a large length to diameter ratio. It is not known how closely this equation describes the convective losses resulting from the flow of fluid around a cylindrical heating coil such as that employed in the present experiments. In any way, the existence of a fully developed boundary layer was not met. This was confirmed by temperature measurements made 6 mm from the heater surface and it was shown that the temperature increased with vertical height. From these considerations, the coefficients calculated from the Sieder-Tate equation would be expected to be significantly lower than the experimental values.

Fig.(2) shows a plot of the heat transfer coefficient against superficial gas velocity for three different liquid rates. As may be seen, introducing the gas into the flowing liquid resulted in an increase in the heat transfer coefficient. This increase was initially rapid but become less marked at the higher gas flow rate. However, the rate of increase in (h) at higher gas velocity was not significant since the major part of gas flow at a high velocity penetrates the liquid column in the form of large bubbles and slugs. These large bubbles and slugs are unable to transfer their heat efficiently into the microscale eddies and only induce an overall circulation of liquid phase, thus not effectively improving the heat transfer. Under these conditions, the coefficients measured in the gas-liquid dispersions were approximately three times those observed with the flowing liquid alone. It may also be noted that the heat transfer coefficient was not sensitive to the liquid velocity in the range studied.

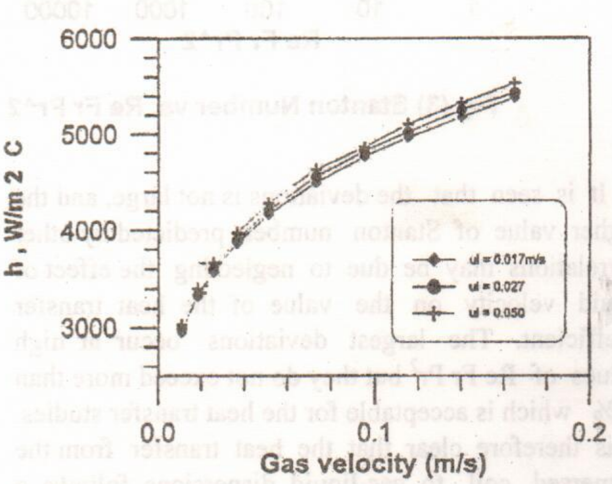

Fig.(2) Heat transfer cofficient vs. gas velocity for different liquid velocities.

A least square analysis of the experimental data yielded the following correlation:

$$h = 8892\, u_g^{0.22}\, u_L^{0.026} \quad \text{.............}(14)$$

There are a good agreement between the present data and those of Kast [8] and Kölbel [7] and other workers[9, 10, 11, 12, 15]. For example, at the gas velocity of 0.1 m/s, Kölbel [7] obtained a coefficient of about 4560 W/m^2 K. the value obtained from equation (14) is 4956 W/m^2 K.

An attempt is made to correlate the experimental data of equation (14) in the form of equation (3). Fig.(3) presents Stanton numbers plotted vs. Re Fr Pr^2 to compare the experimental data of the present work with some of the correlations predicted in previous work. From this figure it is shown that the experimental data of h could also be correlated by:

$$St = 0.116\,(\mathrm{Re}\,Fr\,\mathrm{Pr}^2) \quad \text{......}(15)$$

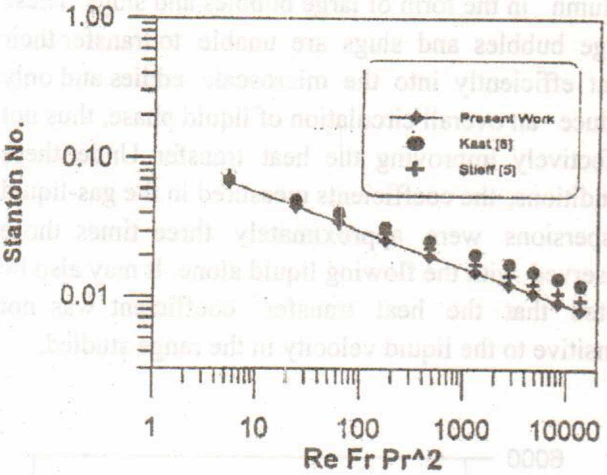

Fig.(3) Stanton Number vs. Re Fr Pr^2

It is seen that the deviations is not large, and the higher value of Stanton numbers predicted by other correlations may be due to neglecting the effect of liquid velocity on the value of the heat transfer coefficient. The largest deviations occur at high values of Re Fr Pr^2 but they do not exceed more than 50% which is acceptable for the heat transfer studies. It is therefore clear that the heat transfer from the immersed coil to gas-liquid dispersions follows a simple and understandable mechanism, which follows the fundamental principles.

Application of Heat Transfer Model

The large heat transfer coefficients achieved in a bubble column are due to agitation of the liquid by the gas bubbles[6]. In addition, the dissipation of energy in the bubble wakes gives rises to considerable small-scale turbulence, which causes high rates of heat removal from the heat transfer surface[2].

The mathematical representation of the model proposed by Deckwer is:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \qquad ......(16)$$

Subjected to the following boundary conditions:

i. $T = T_w \qquad x = 0 \qquad t \geq 0$...(17)

ii. $T = T_B \qquad x > 0 \qquad t = 0$...(18)

iii. $T = T_B \qquad x = \infty \qquad t > 0$...(19)

The last condition requires that the contact time is very short.

Integration of equations (16-19) leads to: [14]

$$q = 2\sqrt{\frac{\alpha}{\pi\theta}}\rho C_p (T_w - T_B) .....(20)$$

Where q is the average heat flux during the contact time θ of the fluid eddy at the heat exchange area. Comparison with the definition of the heat transfer coefficient h yields:

$$h \propto \left(\frac{k\rho C_p}{\theta}\right)^{0.5} .....(21)$$

In order to obtain the contact time θ, Deckwer[2] used the Kolmogoroff's theory of isotropic turbulence. This theory gives the length scale and the velocity scale of the micro eddies in turbulence as:

$$\eta_L = \left(\frac{\nu^3}{\varepsilon}\right)^{0.5} ....(22)$$

$$v = (\nu\varepsilon)^{0.25} ....(23)$$

Where η_L and v are the length scale and velocity scale of the micro eddies respectively, ν is the kinematic viscosity and ε is the energy dissipation rate per unit mass.

The contact time is then calculated as:

$$\theta = \frac{\eta_L}{v} .....(24)$$

Substitution in equation (19) yields:

$$h \propto \left(\frac{k\rho C_p \varepsilon}{\nu^{0.5}}\right)^{0.5} .....(25)$$

The energy dissipation rate per unit mass ε is calculated from:

$$\varepsilon = u_g g ......(26)$$

Introducing this expression in equation (25) gives:

$$h \propto k^{0.5} \rho^{0.75} C_p^{0.5} \mu^{-0.25} g^{0.25} u_g^{0.25} .....(27)$$

Table (3) gives the exponents of the six variables given in equation (27) taken from some of the previous empirical correlations and the present work. When equation (28) is expressed by the following dimensionless form:

$$St = c(\mathrm{Re} Fr \Pr^2)^{-0.25} ....(28)$$

And by plotting the experimental and predicted values of Stanton number vs. $(\mathrm{ReFrPr}^2)^{-0.25}$ as shown in Fig.(4), it is found that these data points can be represented by a straight line expressed as:

$$St = 0.1\,(\mathrm{Re}\, Fr \Pr^2)^{-0.25} .....(29)$$

Table (3): Exponents a_i of parameters from semi-empirical correlations $h \propto k^{a_1} \rho^{a_2} C_p^{a_3} \mu^{a_4} g^{a_5} u_g^{a_6}$

Author	a_1	a_2	a_3	a_4	a_5	a_6
Kast [8]	0.44	0.78	0.50	-0.22	0.22	0.33
Kölbel [7]	0.55	0.78	0.45	-0.33	0.22	0.34
Burkel [12]	0.57	0.76	0.43	-0.33	0.24	0.30
Mersmann [9]	0.50	0.67	0.50	-0.17	0.34	0.33
Hart [3]	0.60	0.75	0.40	-0.35	0.25	0.25
Steif, Weinspach [5]	0.52	0.74	0.48	-0.26	0.26	0.22
Av. value	0.53	0.75	0.46	-0.28	0.25	0.30
Theory, Eq. (28)	0.50	0.75	0.50	-0.25	0.25	0.25
Present work	0.52	0.74	0.48	-0.26	0.26	0.22

This finding shows that the predicted correlation corresponds with all the above equations and also with Deckwer model which depends on the surface renewal model of mass transfer and the Kolmogoroff's theory of isotropic turbulence.

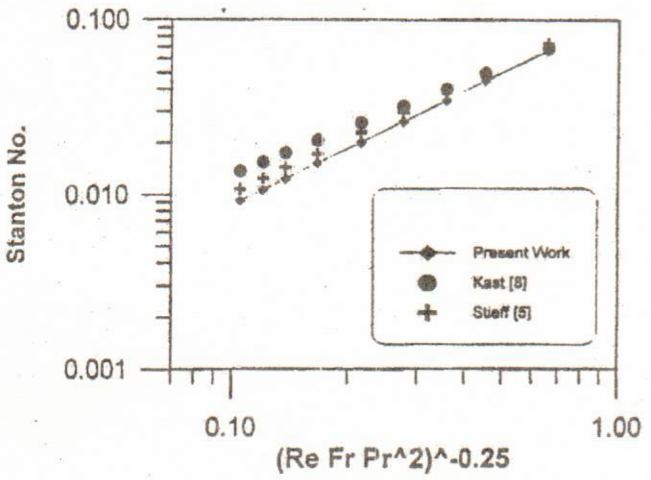

Fig.(4) Test of Eq.(30) with experimental data

Conclusions

The following conclusions can be drawn from the results of the present study:

1. In bubble columns, with immersed heating coil, the heat transfer coefficient initially increased rapidly with gas rate up to a certain limit, after which the increase becomes slower.
2. Liquid velocity had only a small effect on the heat transfer coefficient.
3. The heat transfer coefficients can be successfully estimated from the knowledge of liquid properties and energy input rate in the given system based on Deckwer model.

Nomenclature

A_s	Surface area of the heater	[m^2]
c, m	constants	
C_p	Specific heat at constant pressure	[J/kg K]
d_B	Bubble diameter	[m]
Fr	Froude number, $u_g^2/g\, d_B$	[-]
g	Gravitational acceleration	[m/s^2]
h	Heat transfer coefficient	[W/m^2 K]
k	Thermal conductivity	[W/m K]
Nu	Nusselt number, $h/d_B\, k$	[-]
Q	Heat transferred	[W]
q	Heat flux	[W/m^2]
Re	Reynolds number, $u_g d_B/v$	[-]
St	Stanton number, $h/\rho u_g C_p$	[-]
t	Time	[s]
T	Temperature	[K]
T_B	Temperature in the bulk of liquid	[K]
T_w	Average wall temperature	[K]
u_g	Gas velocity	[m/s]
u_l	Liquid velocity	[m/s]
u_r	Radial velocity component	[m/s]
v	Velocity scale of micro eddies	[m/s]
x	Distance from the surface	[m]
ε	Energy dissipation rate per unit mass	[m^2/s^3]
η_L	Length scale of micro eddies	[m]
θ	Contact time	[s]
μ	Liquid dynamic viscosity	[Ns/m^2]
v	Kinematic viscosity	[m^2/s]
ρ	Liquid density	[kg/m^3]

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