A STUDY OF MASS TRANSFER INTO A LIQUID FALLING FILM IN SPIRAL TUBES USING CO_2 – WATER SYSTEM

A Thesis
Submitted to the College of Engineering of Nahrain University in partial Fulfillment of the Requirements for the Degree of Master of Science in Chemical Engineering

by
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Abstract

Experimental investigation of the mass transfer characteristics of CO_2 – water system falling film in spiral tubes has been done. Several experiments were performed on the average mass transfer liquid film coefficient (K_L) at different variables (tube diameter d = 10 and 20 mm , water flow rate Q_L = 10 – 80 liter/hr , Temperature T = 5,10,15and 20 ºC , CO_2 gas system pressure P = 2,3,4 and 5 bar , and pitch between two turns H = 30,60 and 90 mm or the angle of inclination θ = 8.5, 16.7 and 24.2 deg) at constant coil diameter D = 100 mm , and constant tube length L = 3 m .

The experimental results indicated higher absorption rate of CO_2 in liquids for the case of helically coiled tubes. In this results the film mass transfer coefficient (K_L) increases with increasing film Reynolds number (Re_F), also (K_L) decreases with increasing the pitch between two turns of the coil (or the angle of inclination) . and it decreases with increasing pressure of CO_2 gas at constant other variables, it effect only the value of the equilibrium concentration at the interface between the gas – liquid phase, but the film mass transfer coefficient is in depented on temperature of the system .

Empirical correlation to predict the liquid film mass transfer coefficient, represented by Sherwood number, is derived by using dimensionless analysis for all experiments (384 experiments) to give the following form:-

$$Sh = 1.484*10^{-6} \; Re_F^{\,1.52} \; Sc^{\,0.623} \; Sin\,\theta^{\,-0.606}$$

with R^2 = 0.870 , and the experimental data are within ± 30٪ of the calculated values.

The following equations were derived at different system pressure of CO_2 gas with about ± 10٪ variation:-

P (bar)	The Equation	R^2
2	$Sh = 2.236 * 10^{-6} \; Re_F^{1.51} \; Sc^{0.643} \; Sin\theta^{-0.635}$	0.9184
3	$Sh = 1.799 * 10^{-6} \; Re_F^{1.51} \; Sc^{0.608} \; Sin\theta^{-0.613}$	0.9844
4	$Sh = 1.154 * 10^{-6} \; Re_F^{1.53} \; Sc^{0.595} \; Sin\theta^{-0.628}$	0.9856
5	$Sh = 1.044 * 10^{-6} \; Re_F^{1.53} \; Sc^{0.578} \; Sin\theta^{-0.615}$	0.9870

The overall correlation , including the system pressure effect is given by the following equation :-

$$Sh = 4.314 * 10^{-6} \; Re_F^{1.52} \; Sc^{0.623} \; Sin\,\theta^{-0.606} \; P^{-0.892}$$

With $R^2 = 0.9862$

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Nomenclature

Symbol	***Definition***	***Units***
a	= Constant parameter .	_
A	= Mass transfer area .	m^2
b	= Constant parameter .	_
Ca	= Cabitzi number .	_
C_A	= Concentration of component (A).	mol / liter
C_{Ai}	= Concentration at the inter phase.	mol / liter
C_{AL}	= Concentration of the liquid in the bulk.	mol / liter
C_{Bm}	= Logarithmic of the concentration of the component B.	mol / liter
C_T	= Total concentration .	mol / liter
C*	= Equilibrium concentration of CO_2 in liquid .	mol / liter
D_L	= Diffusivity in the liquid phase	m^2 / s
Dv	= Diffusivity in the gas or vaper	m^2/s
De_F	= Film flow Dean number $\left(= Re_F \left(\frac{d}{D}\right)^{1/2}\right)$.	_
d	= Tube diameter .	m
D	= Coil diameter .	m
f	= film factor fraction .	_
Fr	= Froude number $= \left(\frac{u_F}{(gd)^{0.5}} \right)$	_
g	= grvity cce ertion = 9.81	m/s^2
Ga_F	= Film flow Gallileo number = ($\delta^3 g \, Sin\theta/\upsilon^2$)	_
H	= Pitch between two turns of coil .	m
H	= Henry ’s constant .	atm / mol fraction

j_d = J.factor =($K_L \frac{C_B}{C_T}\left(\frac{\mu}{\rho.D_L}\right)^{0.67}$. –

K_L = Liquid – film mass transfer coefficient m / s

K_G = Gas – film mass transfer coefficient m /s

L = Tube length . m

Nu_F = Nusselt number based on film thickness

(= δ (g $\frac{\rho^2.Sin\theta}{\mu^2}$) $^{1/3}$) –

N_A = Rate of mass transfer . mol/m^2.s

N = Normality . eq.l /m^3

N_1 = Normality of NaOH solution . eq. /m^3

N_2 = Normality of HCL solution . eq. /m^3

P = Pressure . bar

Ps = Vapor pressure . bar

P_{Bm} = Logarithmic mean partial pressure. bar

Q_L = Liquid flow rate . m^3 /s

Re_F = Reynolds number of film (= 4 Γ/μ) –

R = Radius . m

r = Radial direction . –

r_1 = Inner radius of the film . m

Sc = Schmidt number (= μ /D_L ρ). –

Sh = Sherwood number (=K_L δ/D_L) . –

T = Temperature . ºC

t = Time s

us	= Surface film velocity (maximum velocity).	m / s
u_F	= Average film velocity (= Γ / δ ρ) .	m / s
V	= Volume of component .	ml
V_1	= Volume of CO2 solution .	ml
V_2	= Volume of NaOH solution .	ml
V_3	= Volume of HCl solution.	ml
x_A	= Liquid mol fraction of component A .	_
x_A*	= Equilibrium liquid mol fraction .	_
x	= Distance in the direction of transfer or a long surface.	m
y_A	= Vapor mol fraction .	_
y	= Distance perpendicular to surface .	m
z	= Distance in the direction of transfer or a long surface.	m

Greek Letters

δ	= Film thickness .	m
δm	= Effective film thickness for mass transfer .	m
Γ	= Liquid mass flow rate per unit width of surface (or Liquid loading per tube perimeter) (= $\frac{Q_L \rho}{\pi . d}$)	kg /m.s
ρ	= Liquid density.	kg /m^3
μ	= Liquid viscosity.	kg / m.s
υ	= Kinematic viscosity .	m^2 / s
Δ	= Dimensionless concentration (= C*-Cin/C*- Cout).	_

θ	= Angle of inclination with horizontal	_
σ	= Liquid surface tension .	N/m
ϵ_L	= Liquid holdup.	-

CHAPTER ONE

INTRODUCTION

Helical or spiral tubes are used in a variety of applications including food processing , nuclear reactors , compact heat exchangers , gas - liquid contactors , interfacial heat and mass transfer processes in gas absorbers , evaporators , condensers , cooling towers , chemical reactors and medical equipment [1-7].

The coils have many features such as ; compactness, higher rates of momentum, heat and mass transfer, wide range of contact time, less wetting condition, lower pumping and cost due to compactness in comparison to vertical tubes [2].

Falling film refers to thin liquid layer flowing under the influence of gravity over inclined or vertical surface. The kind of flow is greatly complicated due to the disturbing of its free surface by various forces, such as gravity and surface tension. They are responsible for the waviness of the free surface[2].

In spiral tubes, additional centrifugal force influences film thickness, surface profile, velocity profile, and wave types[2]. When fluid flows through a curved pipe, the presence of curvature generates the centrifugal force that acts at a right to the main flow and results in secondary flow. The strength of the secondary flow depends on the curvature of the surface and the flow through curved pipe is much more complex in nature than that of straight pipe [6].

Mass transfer effectiveness in gas-liquid contactors is most often expressed by means of liquid film mass transfer coefficient (K_L).

Considerable experimental data is available in literature on liquid phase controlled mass transfer in case of liquid film falling a long vertical or inclined surface . In such cases the liquid shear is usually absent. However, experimental studies to determine mass transfer coefficient for sheared liquid films, in the case of coils, appears to be scarcely or non- existent [4] .

The literature on mass transfer into liquid falling film has been concerned mainly with the dependence of the mass transfer coefficients on the molecular diffusivity . There are number of mass transfer models exist in literature to simulate the absorption phenomena of gas in liquid , such as the film model , renewal or penetration model , film penetration model , and eddy diffusivity oriented model . But there are limited attempts towards relating the absorption rates to hydrodynamic conditions [4] .

Liquid-phase mass transfer resistance is the most important for those components that are relatively insoluble in the liquid . These components have high value of *equilibrium constant* , and they are the ones which do not condense to any great extent . Hence they will not appear to any great extent in the liquid and they do not have a large interfacial flux at any point of the system. So the literature select oxygen, carbon dioxide for such cases[4] .

Despite varying applications of coils or spiral tubes , literature on the liquid falling film is rather scanty. There are a few publications on the subject, without treatment the conditions of high pressure, without treatment the variation of temperature, and with limited range of the angle of inclination of the coil turns or the pitch between two turns of coil.

The aim of this study is to measure the absorption rates of gas into liquid film in system of falling film down helically coiled tubes represented by liquid film mass transfer coefficient (K_L) and to study the effect of temperature , pressure (not covered in the literature) and the angle of inclination of higher range than that of literature .

CHAPTER TWO

LITERATURE SURVEY

Film flow over flat surfaces or channels and vertical tubes received much attention since the beginning of 20th century . Workers studied, theoretically and experimentally, various parameters affecting film flow. Their general concerns were the characterization of the flow regimes of film and surface conditions, in addition to studying the effect of wall roughness, surface tension, etc. on film flow. Since the mid sixties , extensive literature has been published dealing with wavy gas – liquid interface ; concentrating on the conditions under which waves exist , their measurement or prediction , and analysis of the effect of waves on the processes of heat , mass and momentum transfer [2].

1.2 Flow characteristics of liquid falling film .

For films falling down vertical flat surfaces, as shown in Figure (2-1), or vertical tubes with small film thickness compared to tube radius, laminar flow conditions prevail for the film Reynolds numbers less than about 2000, where the Reynolds number is given by[8]

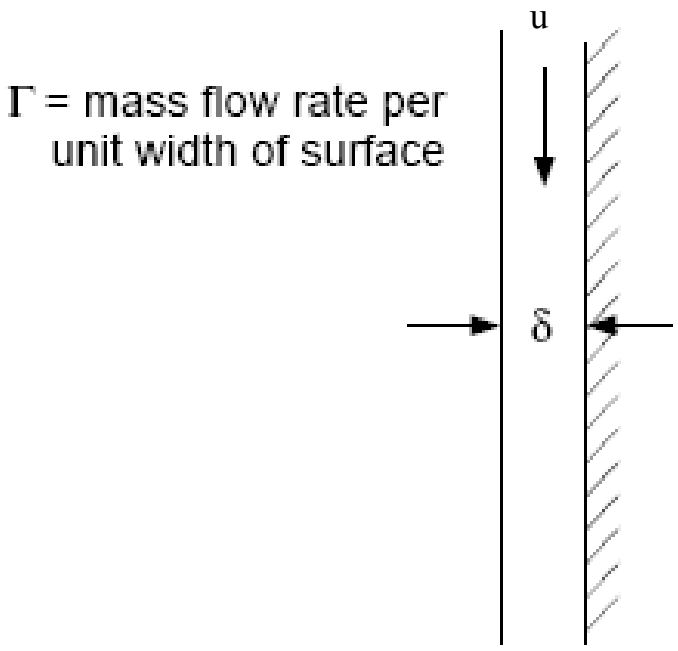
$$Re_F = \frac{4.\Gamma}{\mu} \qquad \ldots(2.1)$$

where

Re_F = Film Reynolds number .

Γ = liquid mass flow rate per unit width of surface.

μ = liquid viscosity.



Figure(2.1) Simple falling film [8]

The liquid film thickness (δ) is given by:-

$$\delta = \left(\frac{3.\Gamma.\mu}{\rho^2.g}\right)^{1/3} \qquad \ldots(2.2)$$

Whereas the average film velocity (u_F) is given by:-

$$u_F = \frac{\Gamma}{\rho.\delta} = \frac{g.\rho.\delta^2}{3\mu} \qquad \ldots(2.3)$$

The downward liquid film velocity profile $u(y)$ where $y = 0$ at the solid surface and $y = \delta$ at the liquid/gas interface is given by:-

$$u(y) = u_s \left[2\frac{y}{\delta} - \left(\frac{y}{\delta}\right)^2 \right] \qquad \ldots(2.4)$$

where

u_s = surface film velocity (maximum velocity)

$$u_s = \frac{\Gamma}{\rho.\delta} = \frac{g.\rho.\delta^2}{3\mu} \qquad \ldots(2.5)$$

$$u_s = 1.5\, u_F \qquad \ldots(2.6)$$

These equations assume that there is no drag force at the gas - liquid interface, such as would be produced by gas flow.

For a surface inclined at an angle θ with the horizontal, the preceding equations may be modified by replacing *g* by *g* sin θ. These equations have generally given good agreement with experimental results for low-viscosity liquids (<0.005 Pa.s) (< 5 cp) [8].

However, Jackson[9] found that the film thicknesses for higher-viscosity liquids (0.01 to 0.02 Pa.s) (10 to 20 cp) were significantly less than predicted by Eq. (2.2).

Derivation of the velocity distribution in a falling thin film according to Nusselt is given by many standard mass transfer textbooks[10-14].

Figure (2-2) shows a schematic representation of the absorption of gases by a falling liquid film flowing along an inclined flat plate. If we assume that the effect of the inertia force is negligibly small, the equation of motion for the falling liquid film can be written as[15]:

$$\rho g \sin\theta + \mu \frac{d^2u}{dy^2} = 0 \qquad \ldots(2.7)$$

The boundary conditions are:

at $y=0$, $u=0$

at $y=\delta$, $\frac{du}{dy}=0$

Assuming that the tangential stress at the surface of the liquid film is negligibly small, by integrating Eq. (2.6) with respect to *y*, we obtain the following equation:

$$u = u_s \left[2\frac{y}{\delta} - \left(\frac{y}{\delta}\right)^2 \right] \qquad \ldots(2.8)$$

$$u_s = \frac{g.\rho.\delta^2 \sin\theta}{3.\mu} = 1.5\, u_F \qquad \ldots(2.9)$$

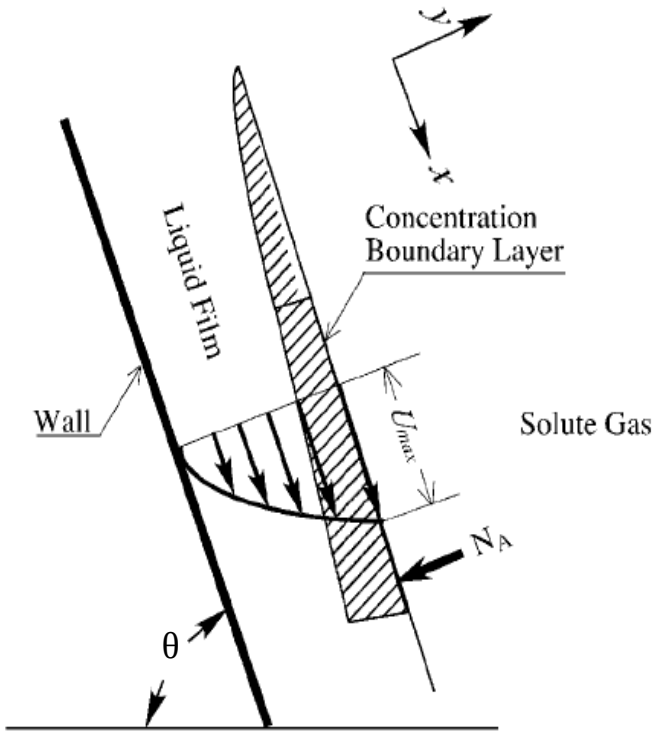
Equation (2.8) is known as *Nusselt's equation* for the velocity distribution in a falling liquid film.

The following equations are obtained from Eq. (2.8), for the flow rate of the liquid per unit width of the plate, Γ [kg m^{-1} s^{-1}] [8] :

$$\Gamma = \int \rho\, u\, dy = \rho\, \delta\, u_F \qquad \ldots(2.10)$$

The thickness of the liquid film, δ [m]:

$$\delta = \left(\frac{3.\Gamma.\mu}{\rho^2 g.\sin\theta}\right)^{1/3} \qquad \ldots(2.11)$$



Figure(2.2) Physical depiction of the absorption gases by a falling liquid film [15]

In turbulent flow, $Re_F > 2000$ for vertical surface ,the film thickness may be estimated to within ±25 percent using the following equation[8]:

$$\delta = 0.304 \left(\Gamma^{1.75} \mu^{0.25} / \rho^2 g \right)^{1/3} \quad \ldots(2.12)$$

Replace *g* by *g* sin θ for a surface inclined at angle θ to the horizontal.

The average film velocity is:

$$u_F = \frac{\Gamma}{\rho.\delta} \quad \ldots(2.13)$$

Brotz (1954)[15] found experimentally that the film thickness for turbulent flow is given by:

$$\delta = 0.172 \left(\frac{\Gamma^2}{\rho^2.g} \right)^{1/3} \quad \ldots(2.14)$$

Which is similar to the finding of Kamei and Oishi (1955)[16].

Park et al. (2004)[17] gives the following correlations;

For laminar flow

$$\delta = (3\, \upsilon^2\, Re_F / 4\, g)^{1/3} \quad \text{at} \quad Re_F \leq 1600 \quad \ldots(2.15)$$

For turbulent flow

$$\delta = 0.144(3\, \upsilon^2 / g)^{1/3}\, Re_F^{8/15} \quad \text{at} \quad Re_F \geq 1600 \quad \ldots(2.16)$$

Abdel-Rahman and Abdullah (2007) [5] studied the flow characteristic of water falling film in spiral tubes. The ratio of the surface film velocity to average film velocity (us/u_F) is found to be less than 1 for low angle of inclination (4 – 8º) where as it increases as the angle of inclination increases reaching a value of about $us/u_F = 1.2$. This small value of the velocity ratio is due to the liquid film rotation in

coil which causes some deletion (compared to vertical tubes) . The ratio of surface film velocity to a verage film velocity was found to be : -

$$us / u_F = 1 \pm 0.2 \quad \ldots(2.17)$$

Where as for vertical falling film [8] , $us / u_F = 1.5$, Eq. (2.6).

The film thickness (δ) is given by the following equation [5] :-

$$\delta = 0.0048\ Re_F^{\ 0.7064} \sin^{-1/3} \theta \quad \ldots (2.18)$$

The film thickness (δ) , was calculated from the data of liquid hold up assuming uniform thickness distribustion

$$\delta = (d / L)\ ((1 - \epsilon_L)^{0.5}) \quad \ldots (2.19)$$

ϵ_L = liquid hold up .

L = length of tube (m) .

d = tube diameter (m) .

Muhommed [3] obtained the following equation for spiral tubes:-

$$Nu_F = 6.5\ Re_F^{\ 0.34} \left(\frac{d}{D}\right)^{0.57} \quad \ldots (2.20)$$

where :-

Nu_F : Nusselt number based on film thickness

$$Nu_F = \delta \left(g\ \frac{Sin\theta \mu^2}{\rho^2} \right) \quad \ldots(2.21)$$

θ = angle of inclination with the horizontal .

Hopf [18] conducted experiments (for water and suger solution) on rectangular channel slope 0.5 – 3 , Re_F = 150 – 600 . Film thickness were

measured by micrometer gauge . The onest of turbulence was marked between Re_F,crit = 250 – 300 , and wall roughness has no effect on Re_F,crit . Except for the smallest depths , the results does not fil the theory of Nusselt.

Nessult gave a theoretical treatement for smooth , laminar two dimensional film flow , and stated as [15,19]

$$\delta = \left(\frac{3\mu^2}{gSin\theta\rho^2} \right)^{1/3} Re_F^{1/3} \quad \ldots(2.22)$$

and correlate experimental laminar data as :-

$$Nu_F = 0.909\ Re_F^{1/3} \quad \ldots(2.23)$$

$$u_F = \left(\frac{gSin\theta\rho}{3\mu} \right) \delta^2 \quad \ldots(2.24)$$

For turbulent flow :-

$$Nu_F = (3\ Re_F)^{1/3} \quad \ldots(2.25)$$

$$f = \frac{6}{Re\,F} \quad \ldots(2.26)$$

where f =film fraction factor

Jeffery 's [20] conducted experiments on channel at small slopes for large range of Re_F**.** A ratio of u_s/u_F of about 1.5 was measured for the laminar region , but decreases to 1.06 in the turbulent region .

Cooper and Willey [21] experimental on films of dilute H_2SO_4 in side vertical tube . Film thickness was determined by drainage technique. Their date and the date of other workers in the literature , were reported and correlated inform of film fraction factor plot . It was found that up to Re_F=

350 , the data of friction factor , f, is in excellent agreement with the equation (2.26).

Kirkbride 's[22] data on film thickness flowing outside a vertical tube , measured by micrometer arrangement , deviate positively from the theoretical film thickness and the date was considered to be the maximum film thickness in a wavy flow .

Fallah et al.[23] reported experimental data for flow of water films inside tube with second phase of air , white oil , stationary and countercurrent kerosene. The results obtained showed that the relation of Nusselt for laminar flow remains valid provided that the quantity ρg in equation (2.24) is replaced by the effective value g ($\rho - \rho$c) .

Where :-

ρc density of second phase .

Jackson [9], measured film thickness by radioisotope tracer method , of many liquids (with and without surfactant).

The waves appearing within the viscous region were shown to appear when Fr exceeds unity . Liquids having a viscosity less than that of water exhibit the film thickness expected for true viscous flow . The velocity profile for flow down a circular tube was derived , and it is found as :-

$$u = \frac{\rho.g}{4.\mu} \left[R^2 - r^2 + 2 (r_1)2 \ln \frac{r}{a} \right] \quad \ldots (2.27)$$

where :-

u = velocity (m/s).

R = tube radius (m) .

r = radial direction .

r_1 = inner radius of the film .

Wilkes and Neddermann[24] determined experimentally the velocity profile in films flowing down vertical tube , by stereoscope photographic method . In smooth flow , Profiles a greed with the theoretical with waves , profile scallered about semi parabola .

Cook and Clark [25] described photographic technique using tracer particles for measurement of fluid velocity distribution . The distribution for fully – developed ripple free flow was found to follow the theoretical Nusselt equation , over Re_F range (75 – 250) .

Dean [26] described a first approximation of the steady motion of in compressible fluid flowing through a coiled pipe with a circular cross – section. He observed that the reduction in the rate of flow due to curvature depends on a single variable when the motion is slow, De, which equal to:

$$De = 2 (Re)^2 \frac{d}{D} \qquad \ldots(2.28)$$

De = Dean number

Fulford s [19] dimensional analysis of film flow showed that , In general, the properties of film may depend on the Reynolds, Weber, and Froude number of the film , and for wavy flow , a strouhal number formed from the

frequency of the surface waves, and various geometrical ratios. An empirical correlation was give for measurements in a channel of slope 7.5° - 90° over the range $30 < Re_F < 300$, in the form of.

$$Nu_F = 1.29 (\sin \theta)^{-0.065} (Re_F)^{0.337} \quad \ldots (2.29)$$

Kapitza [27] gave an experiment treatment for laminar flow and ReF less than 100 as follows:-

$$Nu_F = 0.843 (Re_F)^{1/3} \quad \ldots (2.30)$$

Jawad [2] gave an experiment treatment for turbulent flow as follows :-

$$Nu_F = a (Re_F)^{b} \quad \ldots (2.31)$$

The values of a and b given by many works .Table (2.1) gives the values of a and b for different cases :-

Table (2 .1) Values of parameter of equation (2.31) [2]

Cases	a	b	References
Input tube	0.0682	0.667	Brotz [15]
Input tube	0.1410	0.583	Zhivaikin [28]
Out tube	0.2080	0.533	Brauer [29]
Input tube	0.2660	0.500	Feind [30]
Inclined tube	0.8722	0.470	Jawad [2]

System in which the film thickness varies peripherally , can be characterized by some average film thickness as a function of hydraulic radius and hydraulic depth that define the film boundary . Consequently , it can be concluded as well that the results of film flow in tube of elliptic cross sectional area can be applied equally to film flow in tubes of uniform cross sectional area [2] .

In helical tubes , film thickness increases with the increase of curvature accompanied by a reduction in average within the range of the experimental runs , coiling effect may account for maximum increase in film thickness of 70 ٪ over that of inclined tube . But this increase diminishes gradually in the turbulent region , where the secondary flow intensity is small relative to axial flow intensity [2] .

Pitch within two to three tube diameter in length has no appreciable effect on curvature and hence , has no measurable effect on film thickness.

The transition region in straight inclined tubes is marled between (Re_F = 480 – 600) , which is higher than the angle for vertical tubes (Re_F = 350 – 500) . But the above range coincides with the reported range for full pipe flow (turbulence inception = 2100). In helical tubes , the transition region has shown same delay as concluded by mass transfer experiments. This delay may persist over the entire range of the experimental runs , and therefore further investigation for this point is needed in the future [2].

The experimental results obtained for in straight inclined tubes are correlated empirically in terms of Nusselt number as a function of Reynolds number in the laminar and turbulent regions . In the laminar region , the empirical equation supports the derived theoretical equation. For helical tubes , the experimental results are correlated empirically in terms of Nusselt number of coil over Nusselt

number for straight inclined tube as function of Dean number and some dependency on curvature over that obtained from Dean number [2] .

The reduction in average velocity in helical tubes is accompanied by a reduction in surface velocity at the center of the film , while maintaining a lower values for the ratio of surface velocity to average velocity in straight inclined tube [2] .

Aragaki [31] found a treatment for laminar and turbulent flow for falling film out vertical tube as follows:-

$$Nu_F = [\ 8.92(Re_F)^{5\backslash 2} + 4.04*10^{-5} (Re_F)^{9/2}]^{2/15} \qquad \ldots (2.32)$$

Grabbert [32] found falling film thickness out tube less than that for falling film on flat plate, and for flat plate less for falling film for input tube at constant flow range.

Two – phase air – water mixture flows were studied in helically coiled tubes by Watanabe [33]. The thickness of the water film on the wall of the tubes was measured at different points around the circumference of the tube .

The application of a helical coil in an ammonia-water vapor rectification process for absorption systems was studied numerically by Fernandez –Seara [34]. They discussed the effect of the heat and mass transfer coefficients on the performance of the rectifier .

2.2 Mass transfer fundamental

In steady – state , the rate of mass transfer in the liquid phase is represented by the same basic equation as for gas phase diffusion and may be written as [13] :-

$$N_A = K_L (C_{Ai} – C_{AL}) \quad \ldots (2 . 33)$$

where :-

C_{Ai} = the concentration at the inter phase (kmol / m^3).

C_{AL} = the concentration of the liquid in the bulk (kmol / m^3).

K_L = the liquid – film mass transfer coefficient (m / s).

The rate of diffusion in liquid is much slower than in gases , and mixture of liquids may take a long time to reach equilibrium unless agitated . This is partly due to the much closer spacing of the molecules, as a results of which the molecular attractions are more important. There is at present no theoretical basis for the rate of diffusion in liquids comparable with the kinetic theory for gases.

The mass transfer coefficient predicted by many theories such as , the film theory , the penetration theory , random surface- renewal theory, film- penetration theory and others.

2-2-1 Film Theory Model

The basic equation for dilute concentration is :-

$$N_A = - D_L \left(\frac{dCA}{d\delta} \right) \quad \ldots(2. 34)$$

Equation (2.34) indicates that the concentration distribution is linear, as shown in Figure (2.3), and by integration gives:

$$N_A = - D_L \left(\frac{CA_2 - CA_1}{\delta} \right) \quad \ldots (2.35)$$

where :-

D_L = diffusivity in the liquid phase .

δ_m = effective thickness of liquid film for mass transfer.

Comparing Eq.(2.33) with Eq.(2.35) results the following:

$$K_L = \left(\frac{D_L}{\delta} \right) \qquad \ldots (2.36)$$

Equation (2.35) indicates that the rate of mass transfer in this special case is proportional to the diffusion coefficient and inversely proportional to the thickness of the film. The disadvantage of the film model is that the effective thickness of liquid film for mass transfer is rarely known.

2-2-2 Penetration theory Model

The penetration theory was propounded in (1935) by Higbie[35] , he suggested that the transfer processes was largely attributable to fresh material being brought by the eddies to the interface , where a process of unsteady state transfer took place for a fixed period at the freshly exposed surface . The way in which the concentration gradient builds up as a result of exposing a liquid – initially pure – to the action of a soluble gas as in Fig (2. 4) which is based on Higbie s calculation [19] .

Diffusion of solute (A) a way from the interface (y – direction) is given by the following equation:.

$$\frac{d.C_A}{dt} = D_L \frac{d^2 C_A}{dy^2} \qquad \ldots(2.37)$$

The boundary conditions apply

t = 0	0 < y	$C_A = C_{A0}$
t > 0	y = 0	$C_A = C_Ai$
t < 0	y = ∞	$C_A = C_{A0}$

The solution of the partial differential equation with the boundary condition is given in standard textbook [35] , to give:-

$$N_A = (C_Ai - C_{A\,0}) \sqrt{\frac{D}{\pi.t}} \qquad \ldots(2.38)$$

The average rate of mass transfer is give by :-

$$(NA)\,av = (CAi - CA_0) \sqrt{\frac{D}{\pi}} \frac{1}{t_e} \int_0^{te} \frac{dt}{\sqrt{t}} \qquad \ldots(2.39)$$

$$(NA)\ av = 2\ (CAi - CA0)\ \sqrt{\frac{D}{\pi . t}} \qquad \ldots (2.40)$$

Comparing Eq.(2.35) with Eq.(2.40) results the following:

$$K_L = 2\ (D_L / \pi\ t)^{1/2} \qquad \ldots (2.41)$$

2.2.3 Surface Renewal model

The equation for this model as follows [14]

$$K_L = D_L \, s \qquad \ldots(2 .42)$$

where :-

s = the rate of surface renewal, no data on th rate of surface renewal are currently a vailable

These models found that increasing Reynolds number has only small effect on changing the mass transfer coefficient. The actual experimentally date for mass transfer coefficient did not agree with calculation ones using the stated models. Hameed and Muhammed [4] studied the mass transfer of gases into falling film liquid films in helical coils with the goal to increase the mass transfer coefficients . They correlated their results for the mass transfer in the helical coil in terms of the Schmidt , Sherwood , Dean , and Gallileo numbers , for both laminar and turbulent flow (two separate correlations). Their results showed higher mass transfer coefficient for helical coils compared to straight falling tubes . Furthermore , they determined that increase in higher mass transfer coefficient .

2-3 *Mass transfer correlations*

The rate of mass transfer in the liquid phase in wetted – wall colums is highly dependent on surface conditions . When laminar – flow conditions prevail without the presence of wave formation , the laminar penetration theory prevails . When , however , ripples form at the surface , and they may occur at a Reynolds number exceeding 4 , a significant rate of surface regeneration develops , resulting in an increase in mass transfer rate[8] .

If no wave formations are present , analysis of behavior of the liquid film mass transfer as developed by Hatta and Katori [36] indicates that

$$K_L = 0.422 \left(\frac{D_L . \Gamma}{\rho . \delta^2} \right) \quad \cdots \quad (2.43)$$

where δ is given by Eq.(2 .44),

$$\delta = \left(\frac{3.u.\Gamma}{\rho^2 . g} \right)^{1/3} \quad \ldots (2.44)$$

When length of tube is large or (Γ / ρ δ) is so small that liquid penetration is complete

$$K_L = \frac{11.800 . D_L}{\delta} \quad \ldots \quad (2.45)$$

$$H_L = 0.95\ \Gamma\ \delta / D_L \quad \ldots (2.46)$$

where

H_L = Height of a liquid phase transfer unit, m

A comparison of experimental date for carbon dioxide, oxygen and hydrogen absorption obtained by many authors is indicated in Figure (2.5).[8]

Table (2.2) show the mass transfer correlations for falling film wetted wall column[8].

In general, the observed mass – transfer rates are greater than those predicted by theory and may be related to the development of surface rippling, a phenomenon which increases in intensity with increasing liquid path.[8]

Vivian and Peaceman [37] investigated the characteristics of the CO_2 – H_2O and C_{12} – HCL, H_2O system in a wetted – wall column and found that gas rate had no effect on the liquid – phase coefficient at Reynolds numbers below 2200. Beyond this rate, the effect of the resulting rippling was to increase significantly the liquid – phase transfer rate. The authors proposed a behavior relationship based on a dimensional analysis but suggested caution in its application concomitant with the use of this tupe of relationship. Cognizance was taken by the authors of the effects of column length , one to induce rippling and increase of rate of transfer , one to increase time of exposure which via the penetration theory decreases the average rate of mass transfer in the liquid phase . The dimensionless equation is :-

$$\frac{K_{L.}L}{D} = 0.433\left(\frac{\mu}{\rho.D}\right)^{1/2}\left(\frac{\rho.^2 g.h^3}{\mu^2}\right)^{1.5}\left(\frac{4\Gamma}{\mu}\right)^{0.4} \qquad \ldots(2.47)$$

where

L= length of wetted wall, m

Table (2.2) Mass Transfer correlations for falling films with a

a free surface in wetted wall columns – transfes between Gas and liquid [8]

Situation	Correlation	Comments	Ref
A- Laminar,vertical wetted wall column	$Sh = K_L x/D = 3.41x/\delta$ (First term of infinite series) $\delta = (3\mu\Gamma/\rho^2 g)^{1/3}$	[T] Low rate use with log mean concentration difference parabolic velocity distribution in films $Re_F = 4Q\rho/\pi d \mu < 20$ If $Re_F > 20$, surface waves and rates increases .An approximate solution Dapparent can be used. Ripples are suppressed with awtting agent good to $Re_F = 1200$	[11] [10] [38]
B- Turbulent,vertical wetted wall column	$Sh = K_L d/D = 0.023\ Re^{0.83}\ S_{Cg}^{0.44}$, A cofficient 0.0163 has also been reported using Re where $\upsilon = \upsilon$ of gas relative to liquid film	[E]use with log mean concentration difference for correlations in B and C. Re is for gas. $S_C g$ for vaper in gas use for gases d = tube diameter	[39] [40] [41] [11] [10] [42]
C – Turbulent, vertical wetted wall column with ripples	$Sh = K_L d/D = 0.00814\ Re^{0.83}\ S_C^{0.44}$ $(4Q\rho/\pi d \mu)^{0.15}$ $Sh, = K_L d/D = 0.023\ Re^{0.8}\ S_C^{-43}$	[E] " Rounded" approximation to inclined ripples.Incliudes soild-liquid mass transfer data to find $^{1/3}$ coefficient on Sc.May use $Re^{0.83}$ .use for liquid.	[39] [93] [11]
D-Rectification in vertical wetted wall column with turbulent vapor flow,Johnstone and Pigford correlation	$Sh = K_G d P_{Bm}/D_V \rho = 0.0328$ $(Re)^{0.77}$, $300 < Re < 40000, 0.5 < S_C < 3$ $Re = d\ v\ \rho v/\mu v$, v rel=gas velocity relative to liquid film =3/2 u avg in film	[E]Use logarithmic mean driving force at two ends of column based on four systems with gas-side resistance only.PBm=logarithmic mean partial pressure of nondiffusing species.Bis binary mixture,P= total pressure	[44] [11]

Hikita et .al [45 -46] experimentally two general correlations for mass transfer in wetted wall column:.

$$L\left(\frac{\rho^2 g}{\mu^2}\right)1/3 = 22.836\,(\,Re_F\,)^{0.5}\,Sc^{\,0.38}\,Ga_F^{\,0.04}\left(\frac{\sigma}{72}\right)^{0.15} \qquad \ldots(2.48)$$

For Re_F approximately less than 50

$$\text{And}\quad L\left(\frac{\rho^2 g}{\mu^2}\right) = 2.36\,(\,Re_F\,)^{1.0}\,Sc^{\,0.5} \qquad \ldots(2.49)$$

Where :-

Sc = Schmit number

Ga_F = film flow Gallilo number $= \left(\frac{\delta^3 g.Sin\theta}{\upsilon^2}\right)$

σ = liquid surface tension.

Goodridge and Gartside [47 – 48] experiments on near horizontal channel confirmed the theoretical equation of mass transfer into laminar film for short contact time after making the necessary corrections for the inlet and outlet end effects.

$$\frac{C - C_0}{C_a - C_0} = 3\,\left(\frac{D_L t}{\pi\delta^2}\right)^{0.5} \qquad \ldots(2.50)$$

Where

Ca =surface concentration.

C_0 = intial concentration.

For turbulent flow, Lamourelle and Sandal [49] gave the following correlation using eddy diffusivity model :-

$$Sh = 1.76 * 10^{-5}\ (\,Re_F\,)^{1.506}\,Sc^{\,0.5} \qquad \ldots(2.51)$$

Skelland[10] presents the following two correlations for laminar and turbulent in falling liquid film flow :

For laminar flow

$$K_L\ L/D_L = 0.783\ (\ Re_F\ )^{1/9}\ (\ Sc\ )^{1/3}\ (L^2\rho^2 g\sin\theta/\mu^2\ )^{2/9} \qquad \ldots(\ 2.52\ )$$

For turbulent flow

$$K_L\ L/D_L = 0.327\ (\ Re_F\ )^{2/9}\ (\ Sc\ )^{1/3}\ (L^3\rho^2 g\sin\theta/\mu^2\ )^{2/9} \qquad \ldots(\ 2.53\ )$$

Results of experimental studies of mass transfer can be convently represented by means of the j-factor , originally developed by Chilton and Colburn for heat transfer j_d which they have expressed as [13] .

$$J_d = K_L\ \frac{C_{Bm}}{C_T}\left(\frac{\mu}{\rho.D_L}\right)^{0.67} \qquad \ldots\ (2.54)$$

where :-

$$J_d = j\ .\ \text{factor} = K_L\ \frac{C_{Bm}}{C_T}\ (\frac{\mu}{\rho.D_L})^{\ 0.67} \qquad \ldots\ (2\ .55)$$

$\frac{C_{Bm}}{C_T}$ = the logarithmic of the concentration of the inert component B divided by the total concentration , is introduced because the concentration of component may alter substantially and ($K_L\ C_{Bm}$) has been found to be more nearly constant then K_L .

Several workers have measured the rate of transfer from a liquid flowing down the inside wall of a tube to a gas passing up words . Gilliland and Sherwood[43] have vaporized a number of a liquids into an air stream flowing

up the tube . They worked with a small tube 25 mm diameter (d) and 450 mm long , fitted with calming sections at the top and bottom , and varied the pressure from 14 to 300 KN / m^2 .

The data were plotted logarithmically as :-

$\frac{K_L d}{D_L} \cdot \frac{C_B m}{C_T}$ against Re_F

The following equation was obtained:

$$\frac{K_L}{u} \cdot \frac{Cm}{C_T} \cdot \left(\frac{\mu}{\rho . D} \right)^{0.56} = 0.023 \, \mathrm{Re}^{-0.17} \qquad \ldots (2.56)$$

Eq. (2.54) applies in the absence of ripples which can be responsible for a very much increased rate of mass transfer.

Hameed and Muhammed (2003) found that the Sherwood number is a function of Re_F , Sc and Ga of the liquid film in inclined tube, as given in the following equation [4] :-

For laminar flow

$$Sh = 4.64 * 10^{-3} (Re_F)^{0.35} (Sc)^{0.61} (Ga_F)^{0.14} \qquad \ldots (2.57)$$

For turbulent flow

$$Sh = 2.136 * 10^{-4} (Re_F)^{0.4} (Sc)^{0.65} (Ga_F)^{0.52} \qquad \ldots (2.58)$$

where :-

Sh = Sherwood number = $\frac{K_L \delta}{D_L}$

The two above correlations show that Sherwood number is more dependent on film Reynolds and Gallileo number in turbulent region than in case of laminar

regions , which indicates that mass transfer mechanism in turbulent region is more dependent on convection phenomena[4].

Hameed and Muhammed (2003) found that the Sherwood number is a function of Re_F , Sc and Ga of the liquid film in spiral tube, as given in the following equation [4] :-

For laminar flow region

$$Sh = 1.4 * 10^{-3} (De_F)^{0.13} (Sc)^{0.73} (Ga_F)^{0.5} \quad \ldots(2.59)$$

For turbulent flow region

$$Sh = 1.* 10^{-3} (De_F)^{0.5} (Sc)^{0.54} (Ga_F)^{0.45} \quad \ldots(2.60)$$

Lamorelle and Sandal [49] studied mass transfer coefficient for turbulent flow using many gases such H_2 , CO_2 and He for Re_F between (1300-8300) and found the following equation:-

$$K_L = 0.339 (Re_F)^{0.84} (De_F)^{0.5} \quad \ldots (2.61)$$

$$Sh = 1.76 * 10^{-5} (Re_F)^{1.5} (Sc)^{0.5} \quad \ldots(2.62)$$

Chung and Mills [50] founds that the relation between physics properties in mass transfer coefficient. They used different solution of ethelene cylegole with water to absorption CO_2 and found the equation to calculate the mass transfer coefficient from the equation :.

$$\frac{K_L}{(\upsilon . g)^{1/3}} = (Re_F) (Sc)^{-1/2} f [(\frac{g . \rho^3}{\sigma^3})^{1/4}] \quad \ldots(2.63)$$

Koziol [51] study mass transfer coefficient for falling film on vertical tube using water and CO_2 for Re_F (170 – 2513)

$$Sh = 1.668 (Re_F)^{0.39} (Sc)^{0.5} \quad \ldots(2.64)$$

For $170 < Re_F < 335$

$$Sh = 3.88 \, (Re_F)_{0.24} \, (Sc)_{0.5} \quad \ldots (2.65)$$

For $335 < Re_F < 1080$

$$Sh = 8.92 * 10^{-4} \, (Re_F)^{0.71} \, (Sc)^{0.5} \quad \ldots (2.66)$$

For $1081 < Re_F < 2513$

Won and Mills [52] found a relation for mass transfer coefficient with physics properties and studied the absorption in turbulent flow to gases (O_2, H_2 , CO_2) with water and alcohols, and calculated the mass transfer coefficient from the following equation:-

$$\frac{K_L}{(\upsilon . g)^{1/3}} = 6.97 * 10^{-9} \, (Re_F)^n \, (Sc)^{-j} \, (Ca)^{-2} \quad \ldots (2.67)$$

where :-

$n = 3.49 \, (Ca)^{0.27}$, $j = 0.137 \, (Ca)^{-0.22}$, $Ca = \upsilon . \left(\frac{g . \rho^3}{\sigma^3} \right)^{1/4}$

Ca = Cabitzi number

This equation for $1000 < Re_F < 10000$

$80 < Sc < 2700$

$1.5 * 10^{-3} < Ca < 10.8 * 10^{-3}$

Bin [53] gave equation to calculate the mass transfer coefficient for the same condition as follows:-

$$\frac{K_L}{D^{1/2}} = \left(\frac{2}{\pi} \right) \left(\frac{1}{4} \right)^{3/4} \left(\frac{\upsilon . g . \rho}{\sigma} \right)^{1/2} (Re_F)^{3/4} \quad \ldots (2.68)$$

2.4 Mass transfer coefficient

The mean mass transfer coefficient K_L is calculated from equation for wetted wall column [17].

$$K_L = \frac{Q_L}{\pi(d - 2\delta)L_F} .* LN\left(\frac{C^* - C_{in}}{C^* - C_{out}}\right) \quad \ldots(2.69)$$

where:-

Q_L = liquid volumetric flow rate (m3/s)

d = diameter of tube (m)

L_F = film height (m)

C* = satu ated concentration (mol/liter)

C_{in} = input concentration (mol/liter)

C_{out} = outlet concentration of the mixture (mol/liter)

The general behaviour of absorption process in falling film has been changed by coiling effects as compared to straight tubes . Higher rates of absorption are obtained in the laminar region of film flow in helical tubes. This can be attributed to higher exposed surface area , longer contact time and mixing effect of secondary flow .

Absorption rates increase with increasing curvature . Higher rates are obtained with increasing angle of inclination ; and in helical tubes , torsion reflects the magnitude of this increase better than angle of inclination [2].

1CHAPTER THREE
EXPERIMENTAL WORK

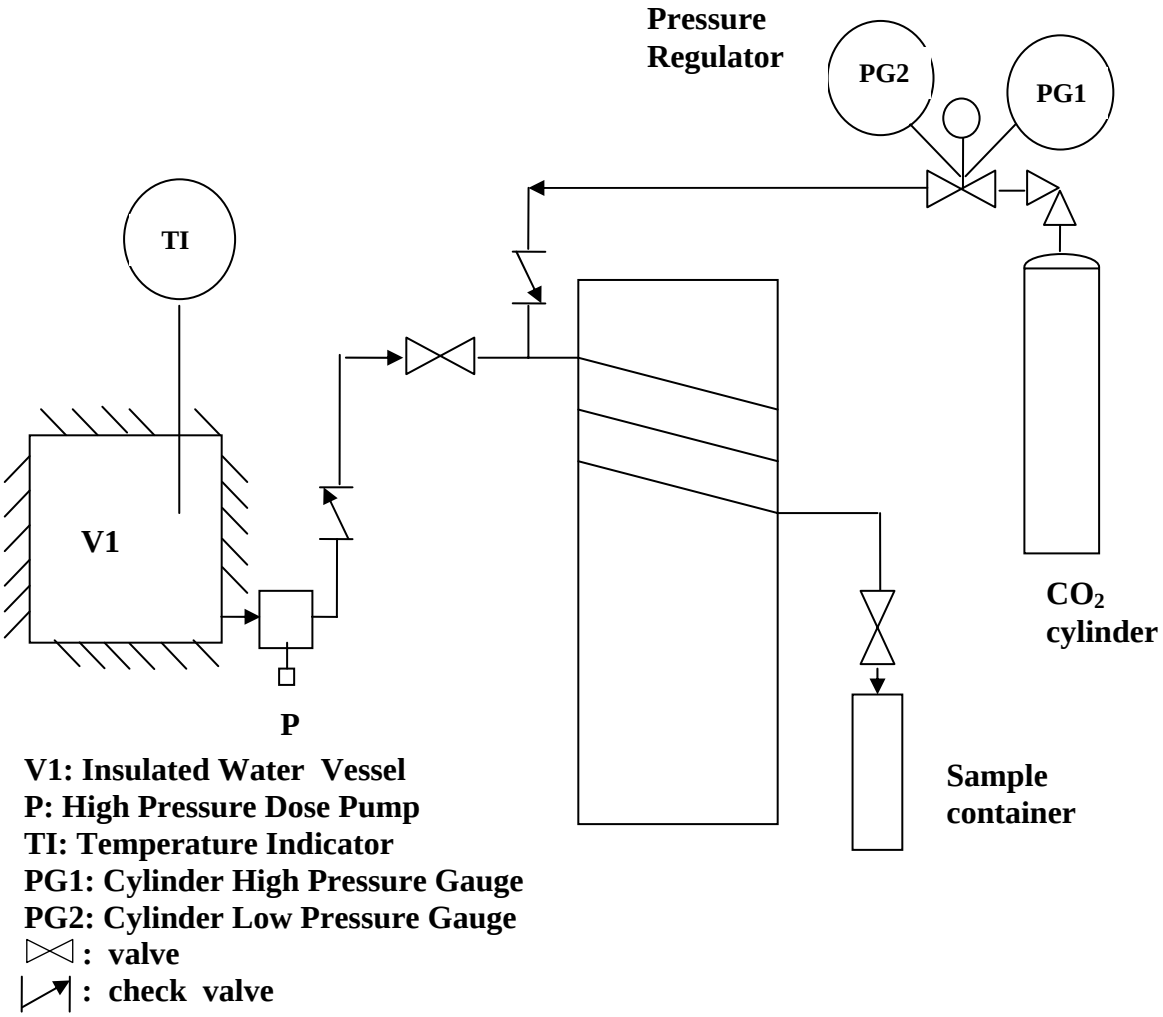
3.1 Experimental Arrangement

Experiments have been conducted using CO_2 – water absorption system in falling film spiral tubes. The schematic diagram of the experimental arrangement is shown in Figure (3.1). The CO_2 gas supplied to the system from a cylinder through a regulator control valve to give a constant pressure condition. High pressure calibrated dosing pump is regulated to give a set of flow rates, 10, 20, 30, and 40 liter/hr for tube diameter, d=10 mm, and the flow rates, 20, 40, 60, and 80 liter/hr for tube diameter, d= 20 mm. Detailed dimensions of the coils used in the experiments are given in Figure (3 . 2) and Table (3 . 1).

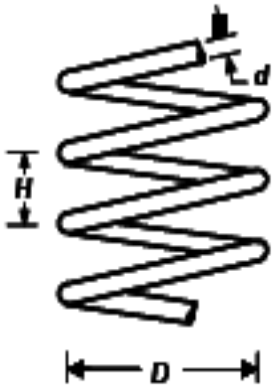
The helical coil was formed by wrapping a flexible transparent plastic tube around a hard PVC pipe (D = 100 mm) in accordance with the required curvatures or angle of inclination.

Experiments have been conducted to measure CO_2 concentration (C) in the outlet of the coil at different water flow rates (Q_L) , different temperature (T= 5, 10, 15, and 20 ^oC) , different CO_2 system pressures (P=2, 3, 4, and 5 bar), and different coil parameters pitch between two turns (H =30, 60, and 90 mm), or the angle of inclination (θ=8.5, 16.7, and 24.2 deg.) and tube diameter (d =10, and 20 mm), with constant tube length (L) of 3 meters and constant coil diameter (D) of 100 mm.

Table (3 . 3) shows the variation of water viscosity (μ) with temperature, whereas Table (3 . 4) shows the variation of CO_2 diffusivity in water (D_L) with temperature .



Figure(3.1) Experimental arrangment



Figure(3.2) Geometry of the test section

Table (3.1) Detailed dimensions of the coils used .

Tube diameter (d)	10 , 20 mm
Coil diameter (D)	100 , mm
Pitch (H)	30 , 60 , 90 mm
Tube length (L)	3 m

Table (3.2) Experimental angle of inclination cases .

D (mm)	H (mm)	tan θ	θ	Sin θ
100	30	0.15	8.5	0.1478
100	60	0.3	16.7	0.287
100	90	0.45	24.2	0.41

Table (3 .3) Variation of water viscosity with temperature[13]

Temperature ºC	μ (mN.s/ m^2)
5	1.57
10	1.31
15	1.14
20	1.0

Table (3 .4) Variation of CO_2 diffusivity in water with temperature [13]

Temperature C	D_L (m^2 /s)*10^{-9}
5	0.906
10	1.105
15	1.293
20	1.5

Where $D_L = \frac{7.7 * 10^{-6} T}{\mu \left(V^{1/3} - V_o^{1/3} \right)}$ …(3. 1)

3 .2 Experimental procedure

The experimental procedure were :-

1 – The temperature of water in the insulated vessel (V_1) was controlled by adding ice cubes and mixing.

2 –The high pressure dosing pump (P) was switched on at selected liquid flow rate. The calibration curve of the pump is given in Fig.(3.3).

3 –The CO_2 pressure was adjusted using the pressure regulating valve connected to the gas cylinder.

4 – After 15 minutes of operation, a sample of the outlet water was taken. Three samples had to be taken.

5 - Liquid samples are analyzed for CO_2 concentration using a standard back titration for NaOH , using HCl and phenolphthalein indicator. A 25 milliliters of liquid sample was taken. The solution is then quenched by 30 milliliters of NaOH solution (0.1 N), then the solution is titrated with HCl solution (0.1 N).

6 - Three liquid samples were analyzed, and the average concentration was then calculated.

CO_2 concentration in water was calculated using the following formula:

$$C_{CO2} = [N_2 V_2 – N_3 V_3] / 2 V_1 \quad \text{…(3.2)}$$

where :-

N_2 , N_3 normality of NaOH and HCl respectively .

V_1, V_2 , and V_3 volume of CO_2 , NaOH and HCl respectively .

The experimental data are shown in Appendix (A).

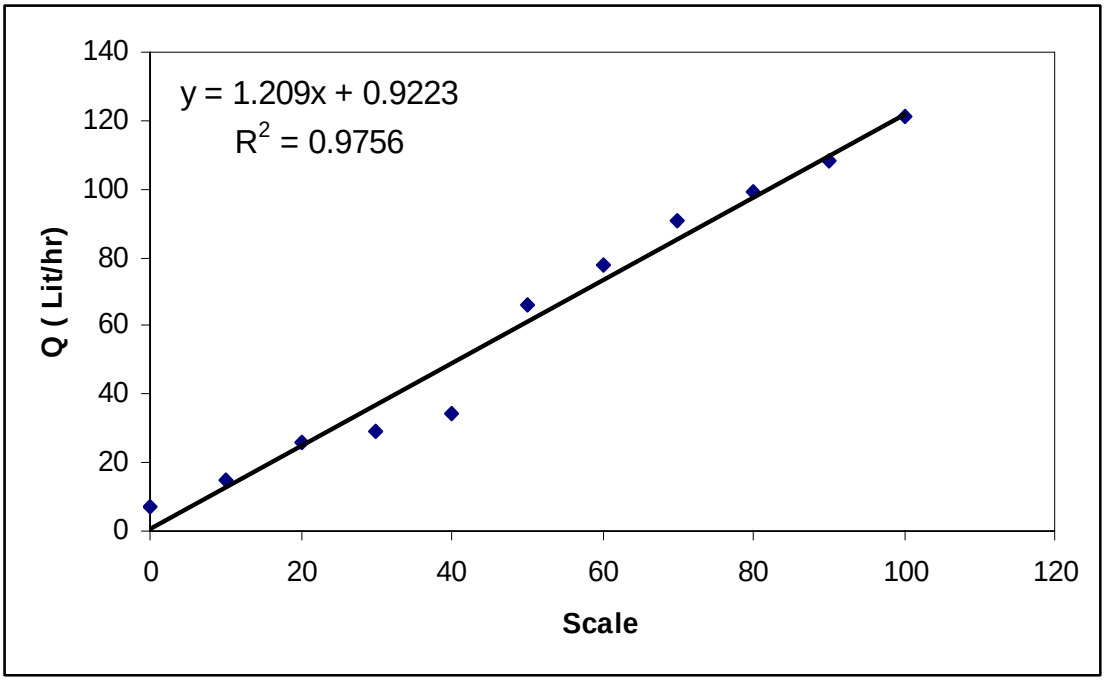


Figure (3.3) Calibration curve of the high pressure dosing pump

3.3 Equilibrium Data [54]

At equilibrium, a component of a gas in contact with a liquid has identical fugacities in both the gas and liquid phase. For ideal solutions, Raoult 's law applies:

$$y_A = Ps / P. x_A \quad \ldots(3.3)$$

where y_A : the mole fraction of component (A) in gas phase.

x_A : the mole fraction of component (A) in liquid phase.

Ps : vapor pressure .

P : total pressure.

For dilute concentrations of most gases, and a wide range for some gases, the equilibrium relationship is given by Henry 's law . This can be written as:

$$P_A = H\, C_A \quad \ldots(3.4)$$

where P_A : partial pressure of component (A).

C_A : mole concentration of component (A), mole/liter.

H : Henry 's constant , depends on the temperature , but relatively independent on the pressure at moderate levels, as shown in Table (3 .5) and Figure (3.3) [54] .

Table (3.5) value of Henry constant for CO_2 – water system at different temperature [54] .

Temperature ºC	0	5	10	15	20
Henry constant (atm/mol- fraction)	728	876	1040	1220	1420

Table (3.6) Equilibrium concentration of CO_2 – water system at different pressure and temperature .

At P = 2 bar

Temperature °C	5	10	15	20
Henry constant(atm/mol frc.)	876	1040	1220	1420
x*(mol fraction)	0.002313	0.001948	0.001661	0.001427
C*(mol/liter)	0.128786	0.108438	0.092412	0.079378

At P = 3 bar

Temperature °C	5	10	15	20
Henry constant(atm/mol frc.)	876	1040	1220	1420
x* (mol fraction)	0.003469	0.002922	0.002491	0.00214
C* (mol/liter)	0.193403	0.162816	0.138734	0.119152

At P = 4 bar

Temperature °C	5	10	15	20
Henry constant(atm/mol frc.)	876	1040	1220	1420
x* (mol fraction)	0.004626	0.003896	0.003321	0.002854
C*(mol/liter)	0.25817	0.2173	0.185132	0.158983

At P = 5 bar

Temperature °C	5	10	15	20
Henry constant(atm/mol frc.)	876	1040	1220	1420
x*(mol fraction)	0.005782	0.00487	0.004152	0.003567
C * (mol/liter)	0.323088	0.27189	0.231608	0.198871

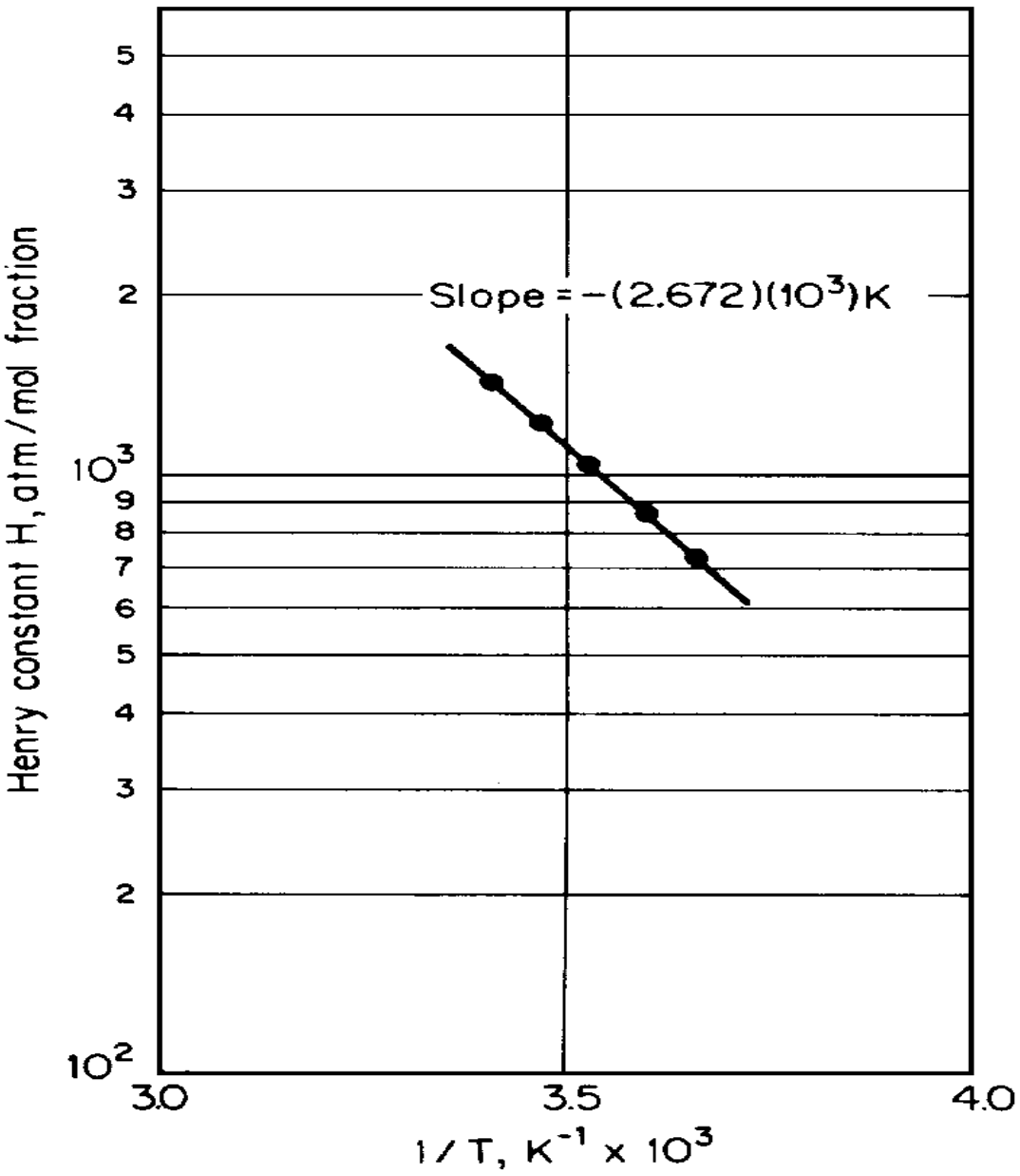


Figure (3.4) Variation of Henry constant with Temperature [54]

3.4 Sample of calculation

3.4.1 Calculation of liquid concentration

To find the concentration of CO_2 in liquid using the equation (3.2):

$$C_{CO2} = (N_2*V_2 - N_3*V_3) /2* V_1 \quad ...(3.2)$$

For experiment number (1) , Table (A1)

NaOH and HCl solutions preparation

$N_2 = 0.08$

$N_3 = 0.1$

$V_1 = 25$ ml

$V_2 = 30$ ml

$V_3 = 12.3$ ml (found by back titration)

$C_{CO2} = (0.08* 30 – 0.1*12.3)/ 2*25$

$= 0.0234$ (mol/liter)

2.4.2 Calculation of Equilibrium liquid concentration

$$x^* = \frac{P_A}{H} \quad \text{(mol fraction)} \quad \ldots(3.5)$$

at T = 5 °C , $H = 876$ (atm / mol fraction) [54]

at $P_A = 2$ bar

$$x^* = \frac{2*1.01325}{876}$$

$= 0.002313$ mol fraction

$$C^* = \frac{nCO_2}{(nH_2O * m.wt / \rho H_2O} \quad \ldots(3.6)$$

Basis : 1 mol

n CO_2 = x*

nH_2O = 1- x*

$$C^* = \frac{x^*}{(1-x^*)*m.wt/\rho H_2O}$$

$$= \frac{0.002313}{((1-0.002313)*18/1000)}$$

= 0.1288 (mol/liter)

3.4.3 Calculation Of Liquid Film Mass Transfer Coefficient (K_L)

To find the mass transfer coefficient (K_L) using the equation (2. 69)

$$K_L = \frac{Q_L}{\pi(d-2.\delta)L_F} * Ln(\Delta)$$

where $\Delta = \frac{C^*-C_{in}}{C^*-C_{out}}$

C in = 0

C out = C_{CO2} = 0.0234 (mol/ liter)

$$\Delta = \frac{0.1288}{(0.1288-0.0234)}$$

= 1.222

$$K_L = \frac{10/3.6}{3.14*(0.01-2*0.00042)*3}$$

= 6.4* 10^{-6} m /s

3.4.4 Calculation Of Film Reynolds Number (Re_F)

To calculate the value of Reynolds number using the following equation:-

$$Re_F = 4 \frac{\Gamma}{\mu} \qquad \ldots(2.1)$$

$$= 4 * \frac{(10/3600)*1000}{3.14*0.01*1.57*10^{-3}}$$

$$= 225$$

3.4.5 Calculation Of Sherwood Number (Sh)

To calculated the value of Sherwood number from the following equation

$$Sh = \frac{K_L \delta}{D_L}$$

The film thickness (δ) is calculated from equation (2. 18)

$$\delta = 0.0048\ Re_F^{\ 0.7064} \sin\theta^{\ -1/3} \qquad \ldots(2.18)$$

$$= 0.0048* (225)^{0.7064} (0.1478)^{-1/3}$$

$$= 0.4162$$

$$Sh = \frac{6.4*10^{-6}*0.4162}{0.906*10^{-9}}$$

$$= 2.965$$

3.4.6 Calculation Of Schmidt Number (Sc)

To calculated the Schmidt number from the following equation

$$Sc = \mu / \rho D_L$$

$$= 1.57* 10^{-3} / 0.906*10^{-9} * 1000$$

$$= 1732.89$$

The experimental data are shown in Tables (A.1) to (A.24), Appendix (A).