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 = ($\delta^3 g$ Sinθ/υ^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 (= $\delta (g \frac{\rho^2 .Sin\theta}{\mu^2})^{1/3}$)	–
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 (= $4 \Gamma/\mu$)	–
R	= Radius .	m
r	= Radial direction .	–
r_1	= Inner radius of the film .	m
Sc	= Schmidt number $\left(= \mu /D_L \rho \right)$.	–
Sh	= Sherwood number $\left(=K_L \delta/D_L\right)$.	–
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 20^{th} 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]

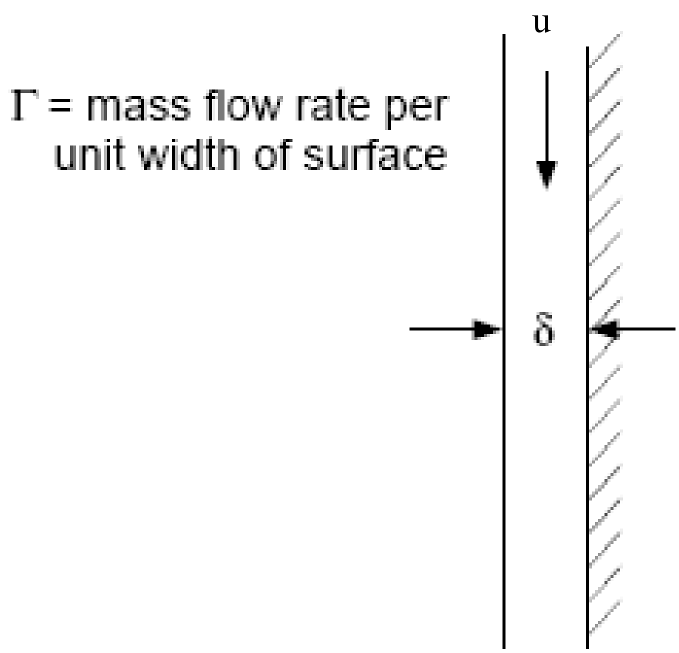
$$Re_F = \frac{4.\Gamma}{\mu} \qquad \text{…(2.1)}$$

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:-

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

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

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

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:-

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

where

u_s = surface film velocity (maximum velocity)

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

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

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 $g \sin\theta$. 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:

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

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

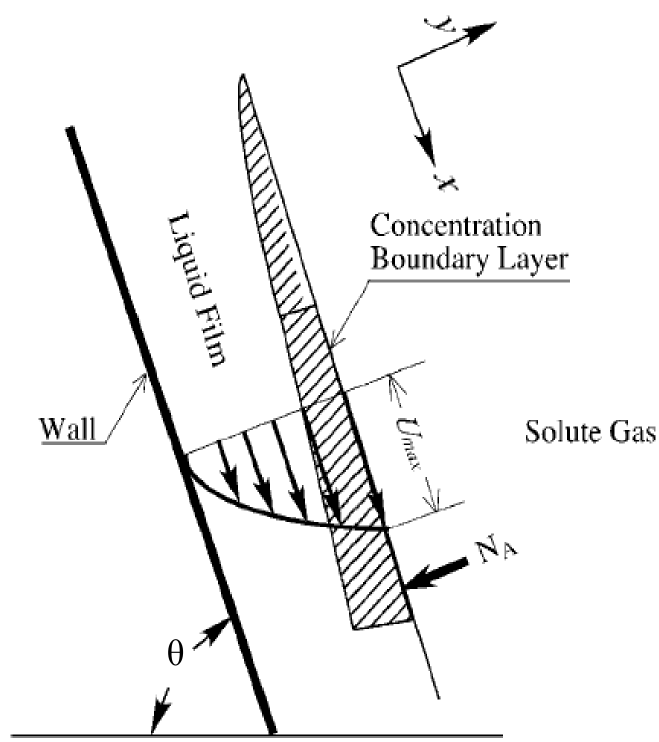
Equation (2.8) is known as *Nusselt's equation* for the velocity distribution in a falling liquid film.

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]:

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

Replace g by $g \sin\theta$ for a surface inclined at angle θ to the horizontal.

The average film velocity is:

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

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

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

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

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

For laminar flow

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

For turbulent flow

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

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 (u_s/u_F) is found to be less than 1 for low angle of inclination (4 – 8°) where as it increases as the angle of inclination increases reaching a value of about u_s/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 : -

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

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] :-

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

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

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

ϵ_L = liquid hold up .

L = length of tube (m) .

d = tube diameter (m) .

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

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

where :-

Nu_F : Nusselt number based on film thickness

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

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]

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

and correlate experimental laminar data as :-

$$Nu_F = 0.909\ Re_F^{1/3} \qquad \text{… (2.23)}$$

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

For turbulent flow :-

$$Nu_F = (3\ Re_F)^{1/3} \qquad \text{… (2.25)}$$

$$f = \frac{6}{Re F} \qquad \text{…(2.26)}$$

where f =film fraction factor

Jeffery 's [20] conducted experiments on channel at small slopes for large range of Re_F**.** A ratio of us/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.

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

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

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

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

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

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] :-

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

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 :-

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

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

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

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:

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

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

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

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

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

where δ is given by Eq.(2 .44),

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

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

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

$$H_L = 0.95\, \Gamma\, \delta / D_L \quad \text{... (2.46)}$$

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 υ=υ of gas relative to liquid film	[E]use with log mean concentration difference for correlations in B and C. Re is for gas. S_Cg 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 ρv/μv, 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:.

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

For Re_F approximately less than 50

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

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.

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

Where

Ca =surface concentration.

C_0 = intial concentration.

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

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

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 :-

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

$\frac{C_{Bm}}{C_T} =$ 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 :-

$$\frac{K_{L.}d}{D_L}.\frac{C_B m}{C_T} \quad \text{against } Re_F$$

The following equation was obtained:

$$\frac{K_{L.}}{u}.\frac{Cm}{C_T}.\left(\frac{\mu}{\rho.D}\right)^{0.56} = 0.023\,Re^{-0.17} \qquad \text{… (2.56)}$$

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

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

For turbulent flow

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

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

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

For turbulent flow region

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

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:-

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

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

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 :.

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

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

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

For $170 < Re_F < 335$

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

For $335 < Re_F < 1080$

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

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:-

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

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:-

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

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

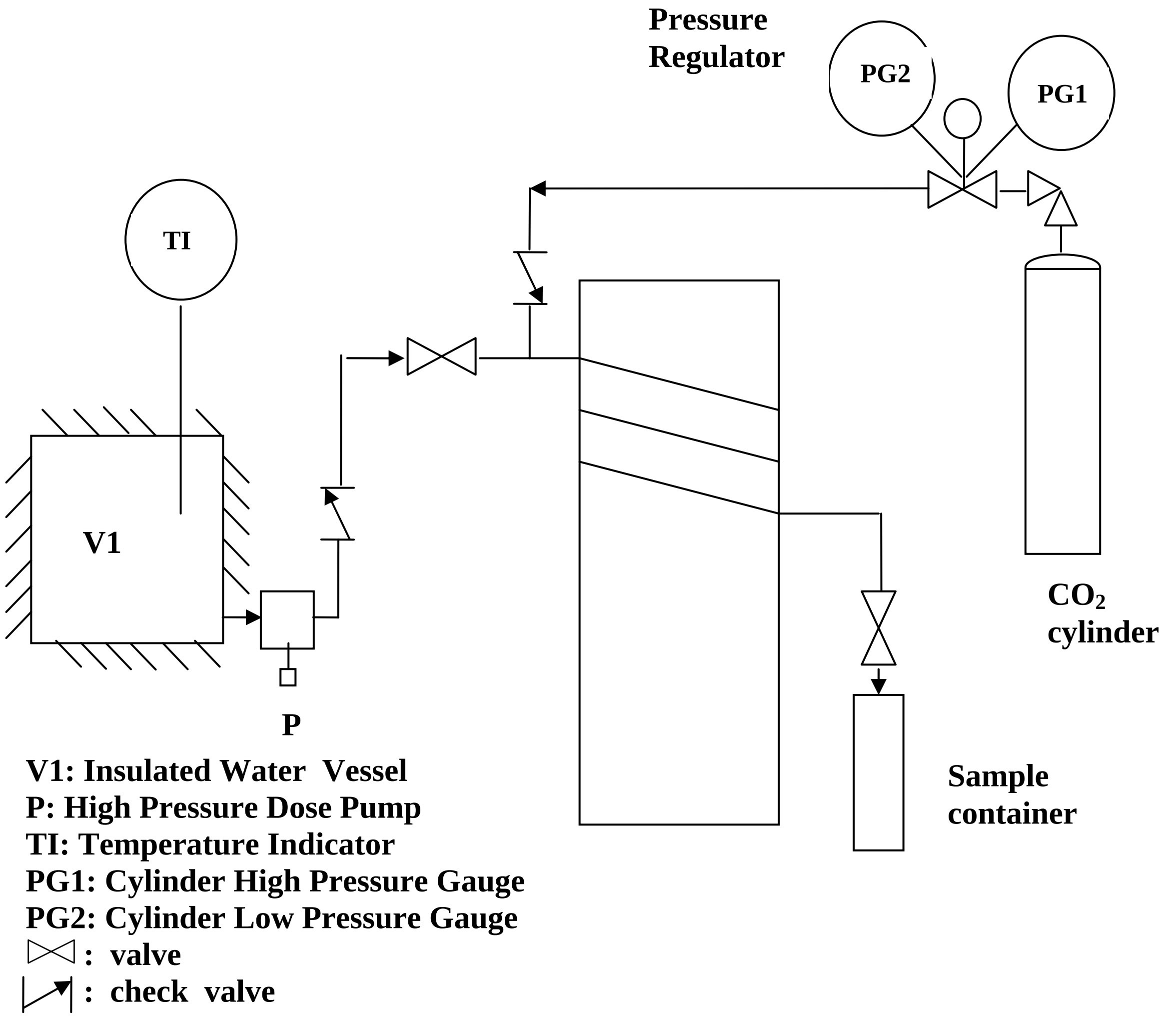
3.1 Experimental Arrangement

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).

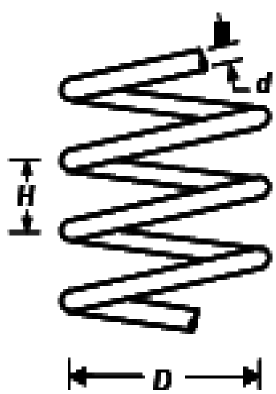
The helical coil was formed by wrapping a flexible transparent plastic tube around a hard PVC pipe (D = 100 mm) in accordance with the required curvatures or angle of inclination.

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 $D_L = \dfrac{7.7*10^{-6}T}{\mu\left(V^{1/3} - V_{\circ}^{1/3}\right)}$ …(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:

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

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).

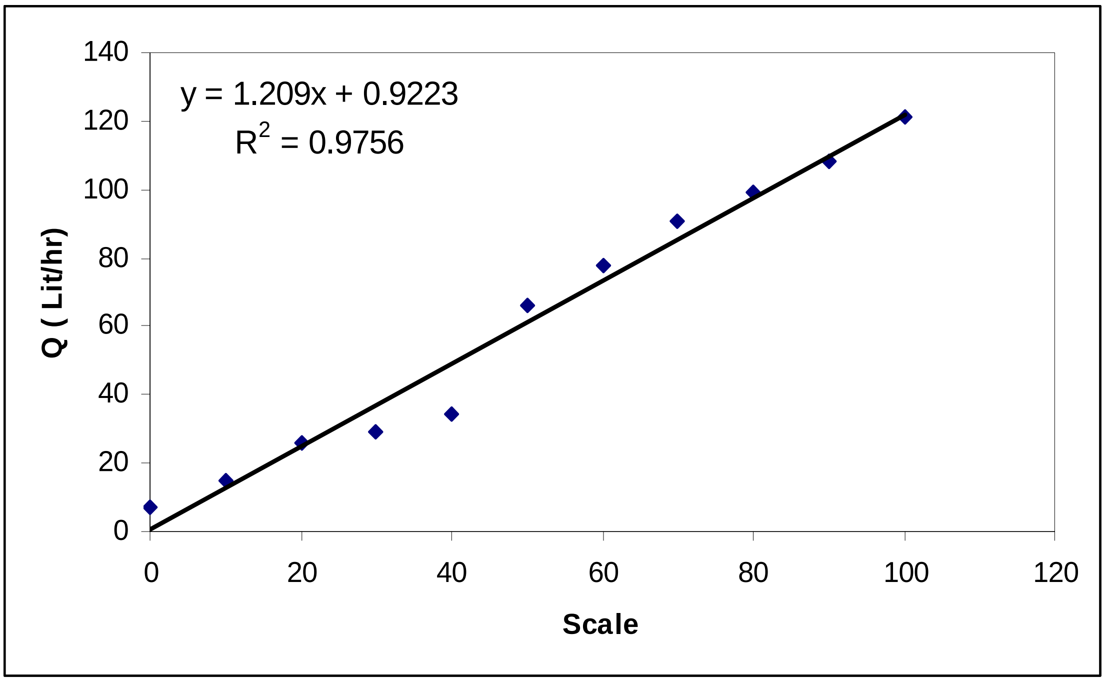


Figure (3.3) Calibration curve of the high pressure dosing pump

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:

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

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:

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

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

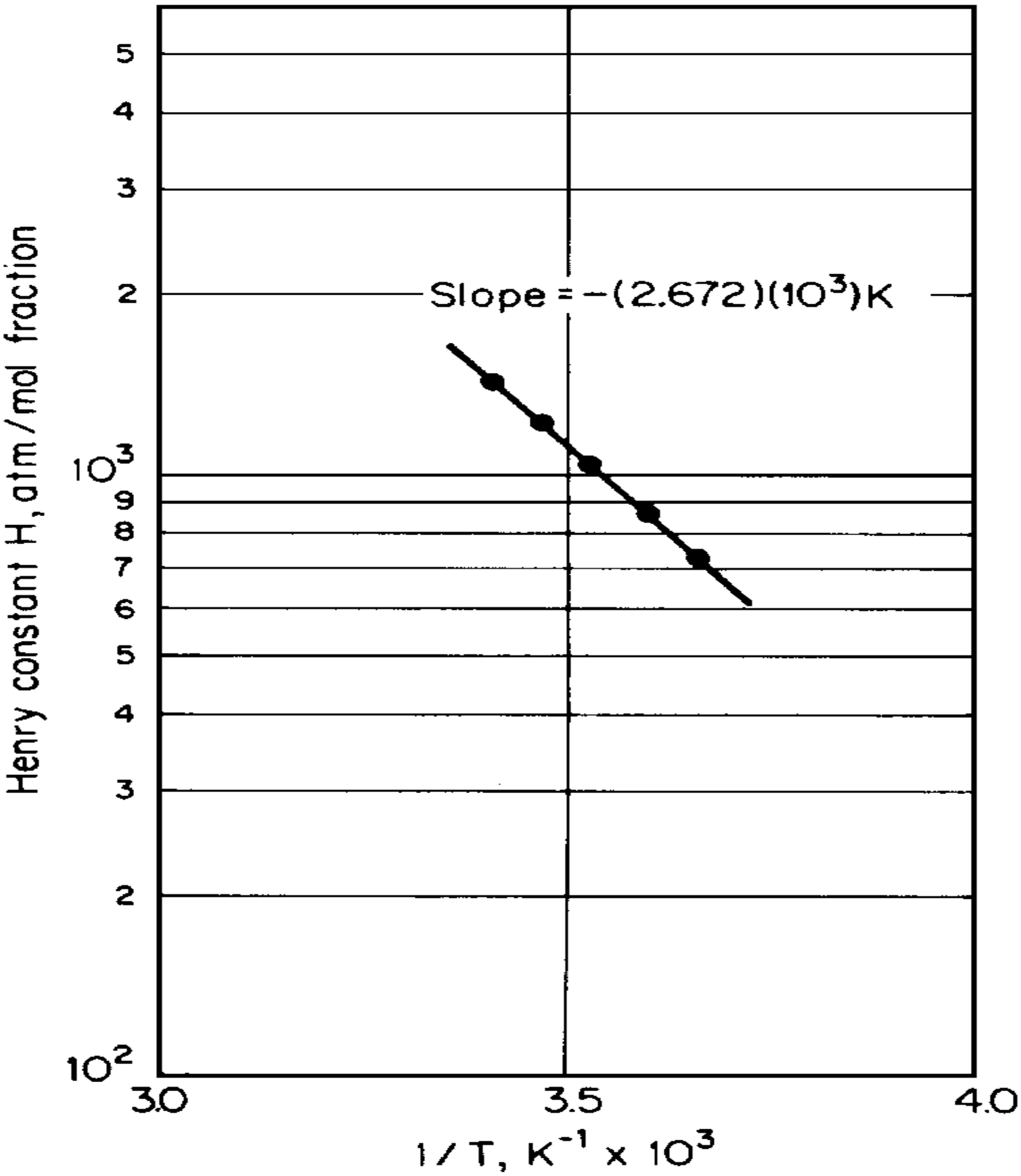


Figure (3.4) Variation of Henry constant with Temperature [54]

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):

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

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

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

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

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

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:-

$Re_F = 4 \dfrac{\Gamma}{\mu}$ …(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)

$\delta = 0.0048\ Re_F^{\ 0.7064} \sin\theta^{\ -1/3}$ …(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).

CHAPTER FOUR
RESULTS AND DISCUSSIONS

Several experiments were performed for the mass transfer of CO_2 – water absorption in spiral tubes. The experimental data are shown in Table (A . 1) to Table (A . 24) , Appendix (A) .

The results were represented by the liquid film mass transfer coefficient (K_L), Sherwood number (Sh) , Schmidt number (Sc) , film Reynolds number (Re_F) , and the Sine of angle of inclination (Sin θ).

There is a limitation in the equipment for the liquid flow rates , Reynolds numbers and the other variables , the range are ;

Q_L = up to 40 Liter / hr for d = 10 mm

Q_L = up to 80 Liter / hr for d = 20 mm

Re_F = 225 – 1400 θ = 8.5 – 24.2 deg.

$K_L = 6 * 10^{-6} – 41 * 10^{-6}$ m/s Sh = 2 – 42

Sc = 667 – 1733

4 .1 Effect of film flow Reynolds number (Re_F)

All the Figures , presented in this work for the liquid film mass transfer coefficient (K_L) versus the film Reynolds number (Re_F), Figures (4.1) to (4.80) show that the mass transfer coefficient increases with increasing film Reynolds number, in the range of variable studied .These result agree well with the literature of Jawad [2] , and Hameed and Muhammed[4] . The exception is that there is no distinguish between the two regimes laminar and turulent in the present work. The expected regime in the present work is wavy laminar.

4 .2 Effect of the pitch between two turns of the coil (**H** *) (or the angle of inclination (θ))*

Figures (4 . 1) to (4 .32) show the effect of the pitch between two turns of the coil (or the angle of inclination) on the liquid film mass transfer coefficient (K_L) . The Figures show that the liquid film mass transfer coefficient decreases with increasing the pitch between two turns (H) from 30 mm to 60 mm or increasing the angle of inclination (θ) from 8.5º to 16.7º , where as , at higher angle (at H =90 mm and θ=24.2º, the mass transfer coefficient increases or tend to be unchanged. Hameed and Muhammed [4] found there was no real effect of the angle of inclination on K_L for their range studied (3 – 5 º) .

This may be explained by the fact that the mass transfer rate, which is used to calculate the mass transfer coefficient, depends on many variables. The interaction effects of the following variables leads to these results:-

i – Mass transfer contact area and its variation.

ii – Contact time between two phases and its variation.

iii – Film thickness and its variation.

The same trend was noticed for the variation of Sherwood number (Sh) verses film Reynolds number (Re_F), at different angle of inclination (θ), as shown in Figure (4.81)and (4.82).

4 . 3 Effect of system pressure of CO_2 gas (P).

Figure (4 . 33) to (4 . 56) show the effect of system pressure of CO_2 gas on the liquid film mass transfer coefficient (K_L) . The figures show that K_L decreases with increasing the CO_2 gas pressure at constant other variables , i.e K_L inversely proportional to the pressure .

Increasing the system pressure (P) does not affect the liquid physical properties , it affects only the value of the equilibrium concentration at the interface between the gas – liquid phases . This increases the concentration driving force of the system which increases the rate of mass transfer .

The same trend was noticed for the variation of Sherwood number (Sh) verses film Reynolds number (Re_F), at different system pressure of CO_2 gas (P), as shown in Figure (4.83) and (4.84).

4.4 Effect of Temperature (T)

Figures (4 . 57) to (4 .80) show the effect of system temperature on the liquid film mass transfer coefficient (K_L) , The Figures show that the mass transfer coefficient is independent of temperature in most cases. A decrease of (K_L) with increasing the temperature especially at 20 ^oC was noticed. This may be explained by the fact that the temperature affects the physical properties and the equilibrium condition of the system and consequently affect the concentration driving force which balances the effects on the liquid film mass transfer coefficient (K_L).

The experimental results for the system temperature were also represented by the variation of Sherwood number (Sh) with the film Reynolds number (Re_F) at different temperatures as shown in Fig. (4. 85) to (4.87).The Fig. show that the Sherwood number decreases with increasing the temperature.

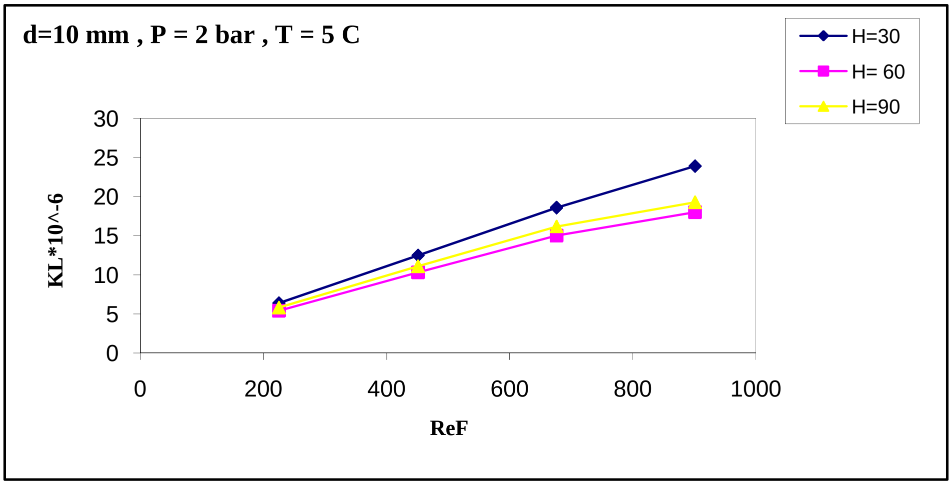


Figure (4.1) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 10 mm , P = 2 bar , T = 5 C).

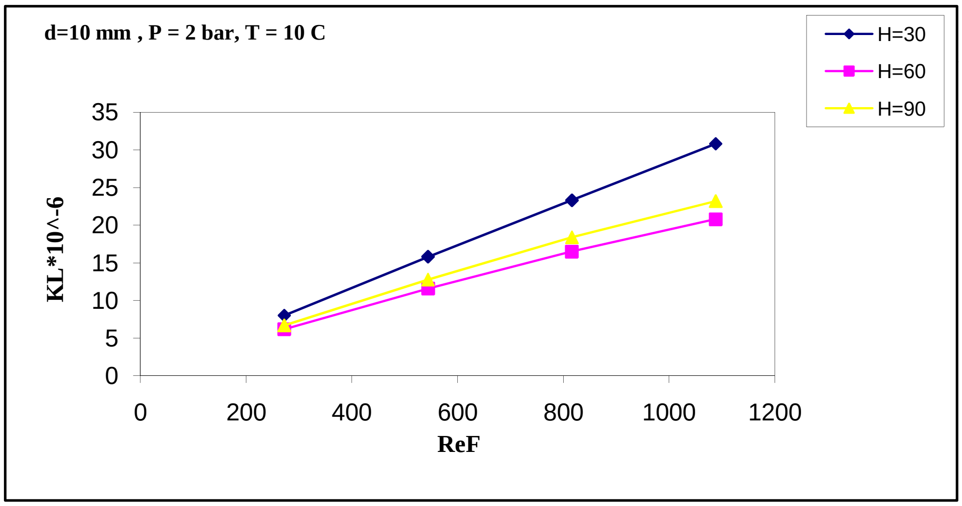


Figure (4.2) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 10 mm , P = 2 bar , T = 10 C).

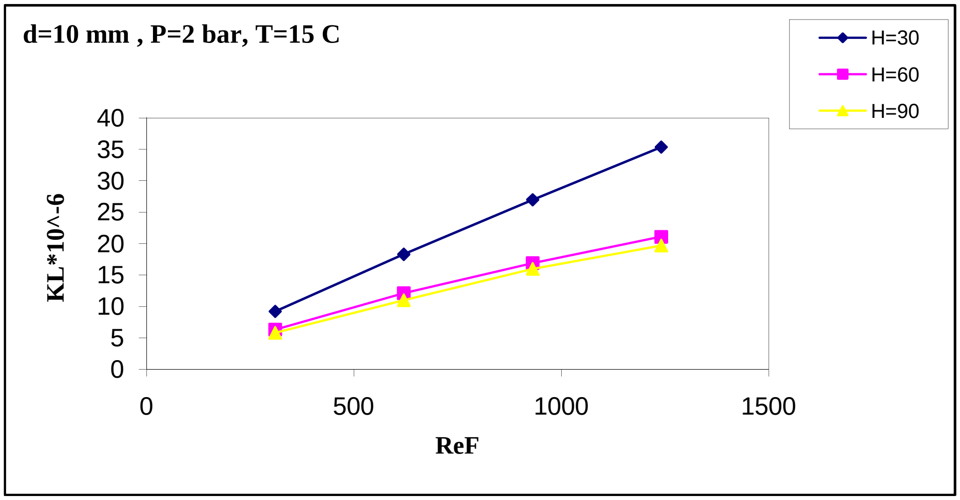


Figure (4.3) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 10 mm , P = 2 bar , T = 15 C).

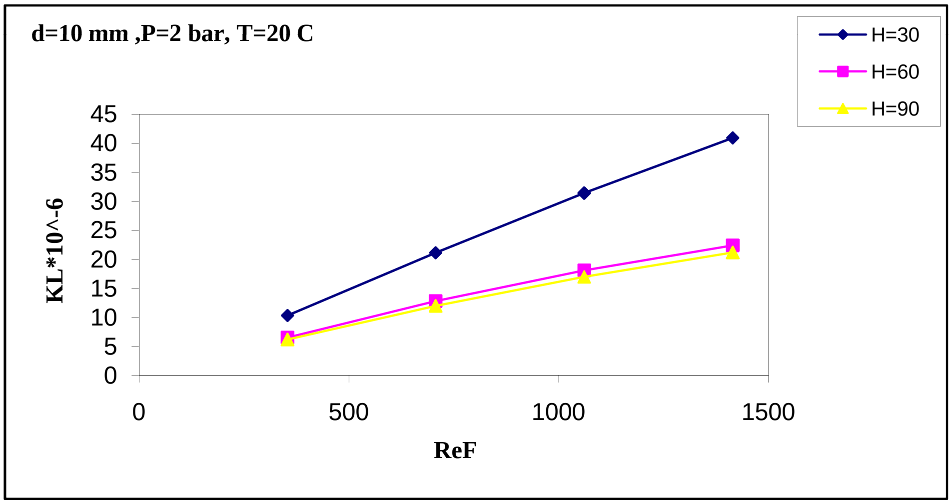


Figure (4.4) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 10 mm , P = 2 bar , T = 20 C).

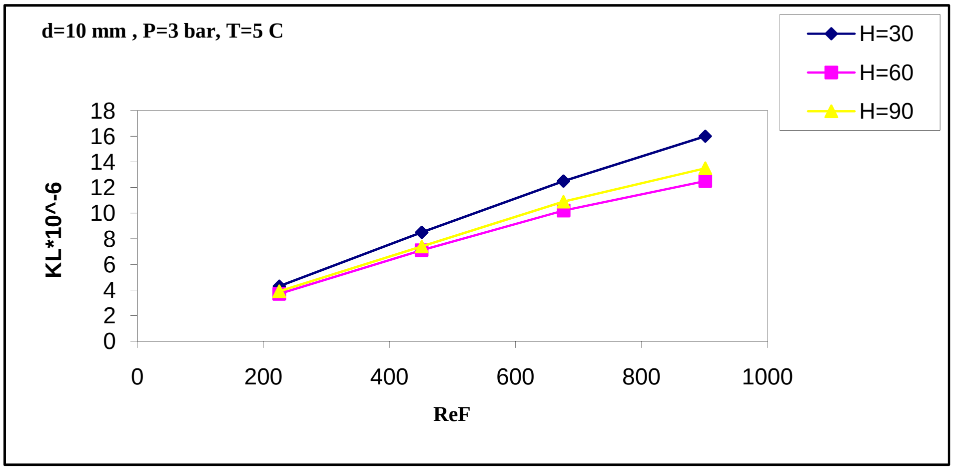


Figure (4.5) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 10 mm , P = 3 bar , T = 5 C).

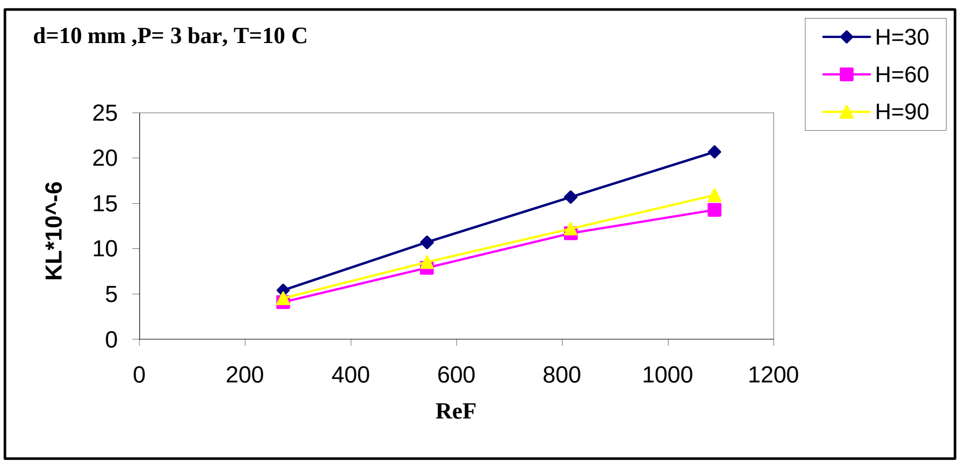


Figure (4.6) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 10 mm , P = 3 bar , T = 10 C).

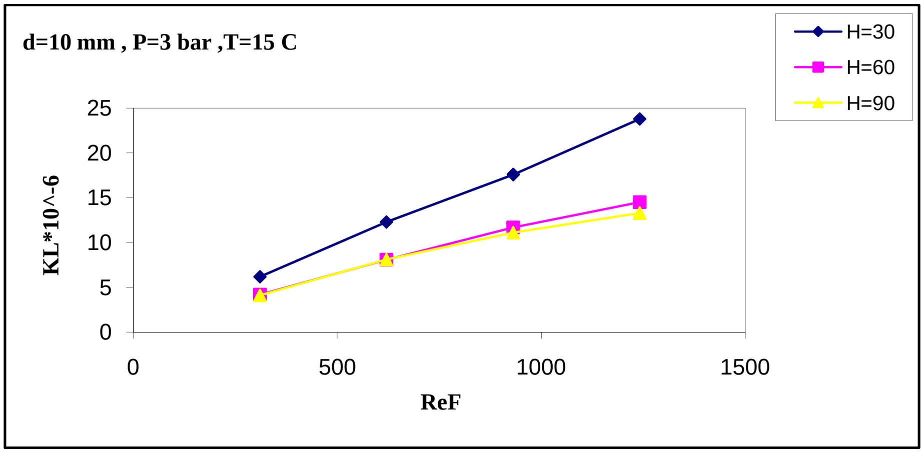


Figure (4.7) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 10 mm , P = 3 bar , T = 15 C).

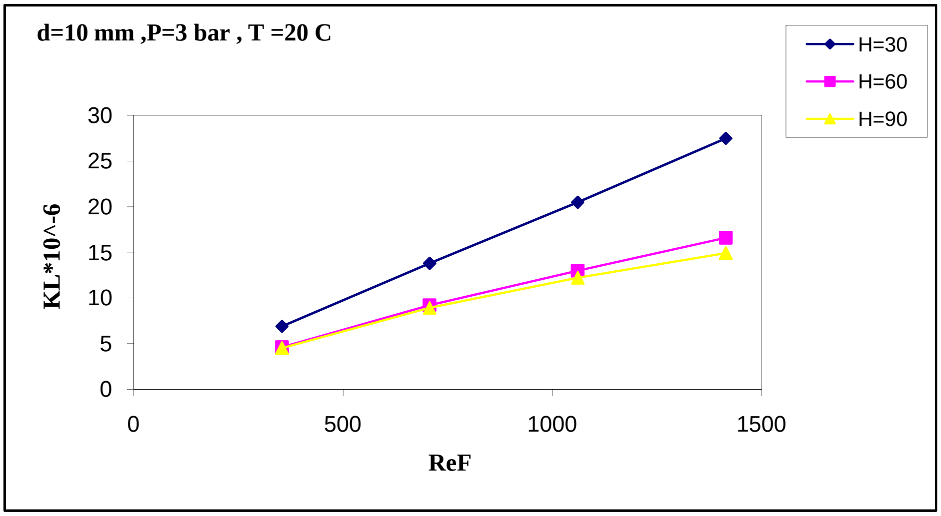


Figure (4.8) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 10 mm , P = 3 bar , T = 20 C).

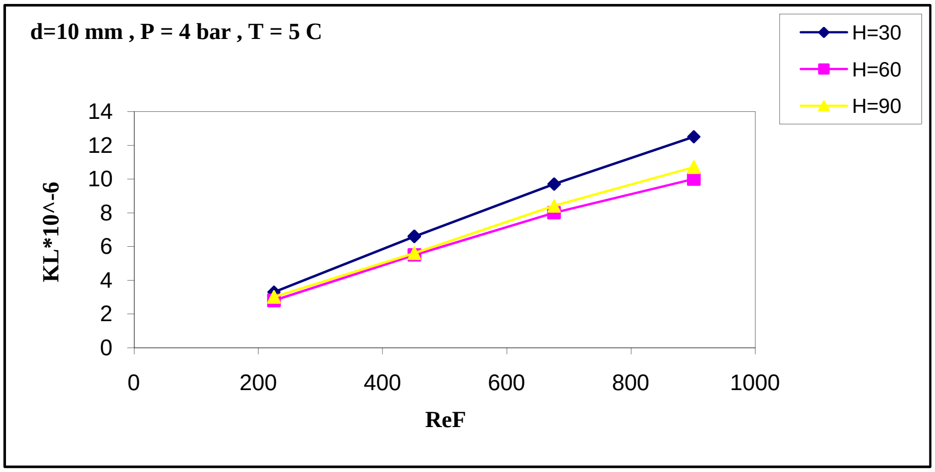


Figure (4.9) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 10 mm , P = 4 bar , T = 5 C).

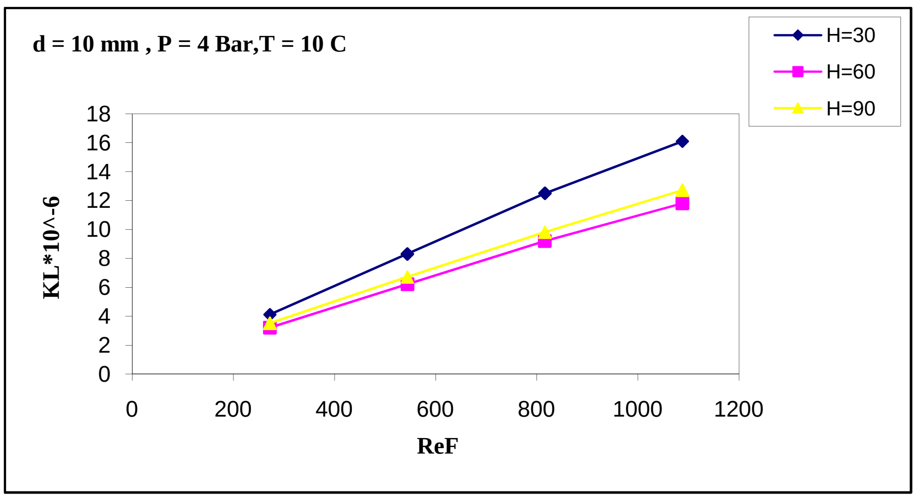


Figure (4.10) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 10 mm , P = 4 bar , T = 10 C).

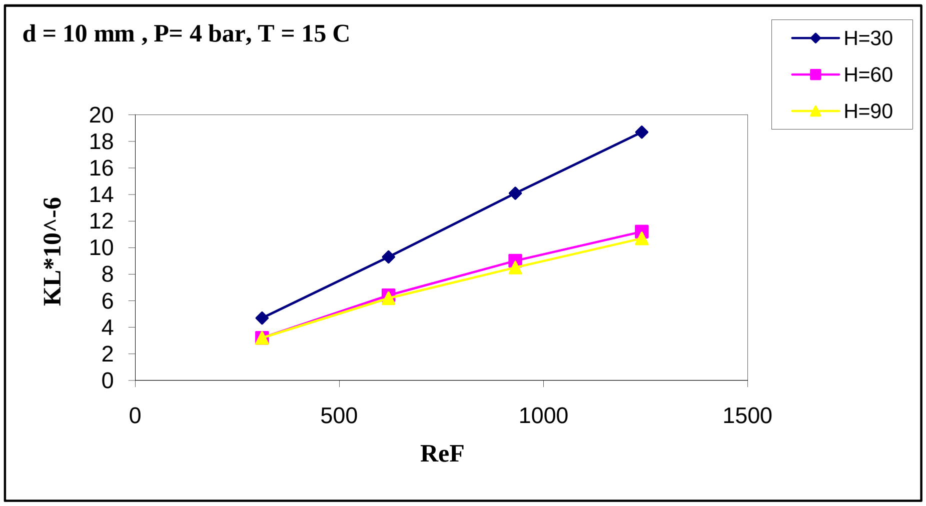


Figure (4.11) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 10 mm , P = 4 bar , T = 15 C).

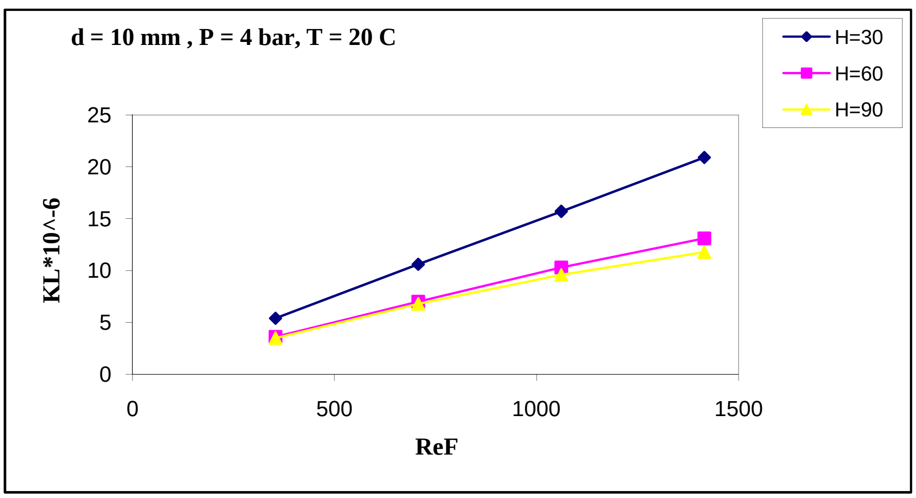


Figure (4.12) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 10 mm , P = 4 bar , T = 20 C).

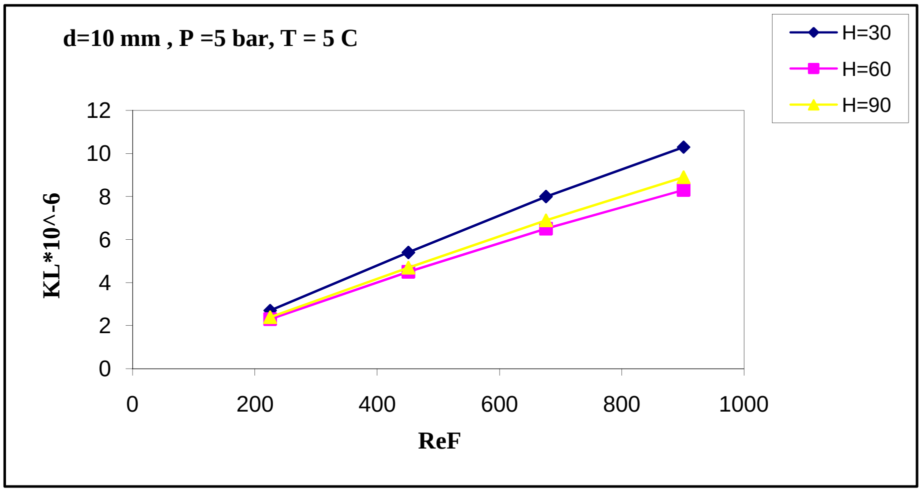


Figure (4.13) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 10 mm , P = 5 bar , T = 5 C).

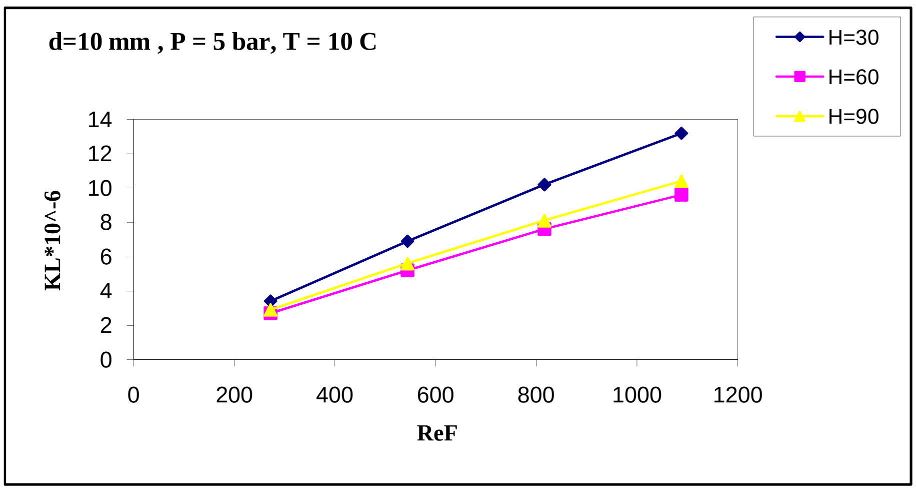


Figure (4.14) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 10 mm , P = 5 bar , T = 10 C).

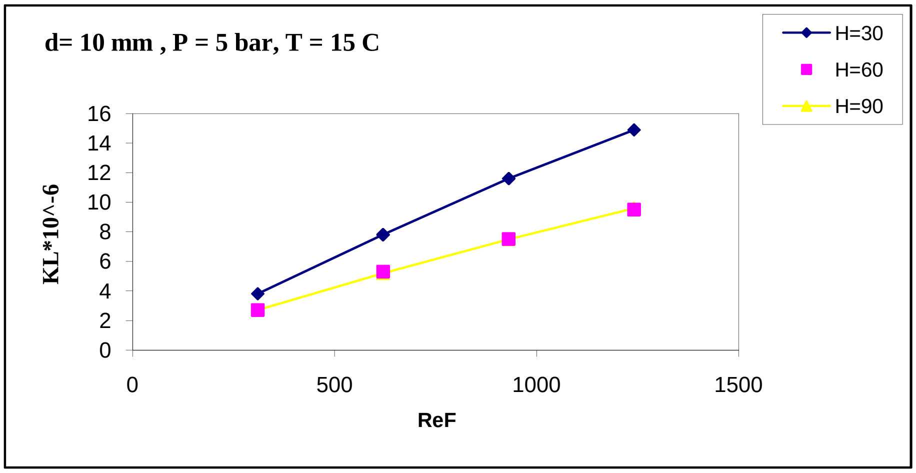


Figure (4.15) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 10 mm , P = 5 bar , T = 15 C).

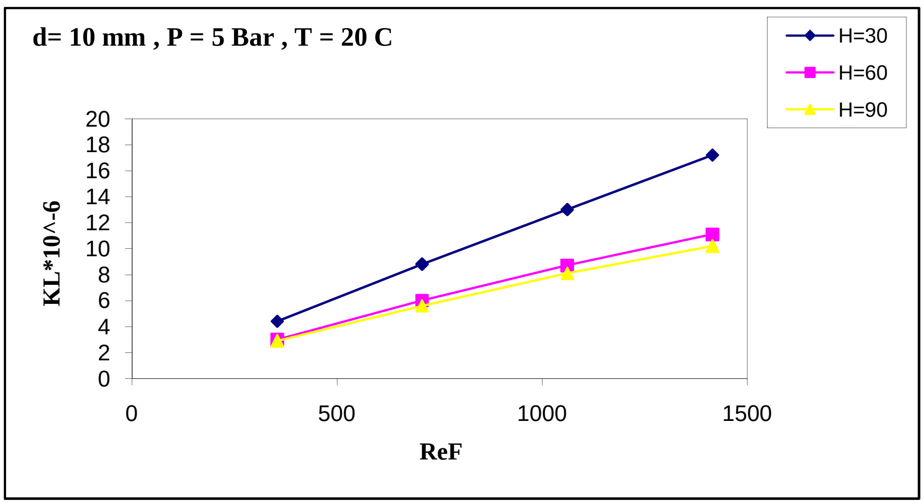


Figure (4.16) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 10 mm , P = 5 bar , T = 20 C).

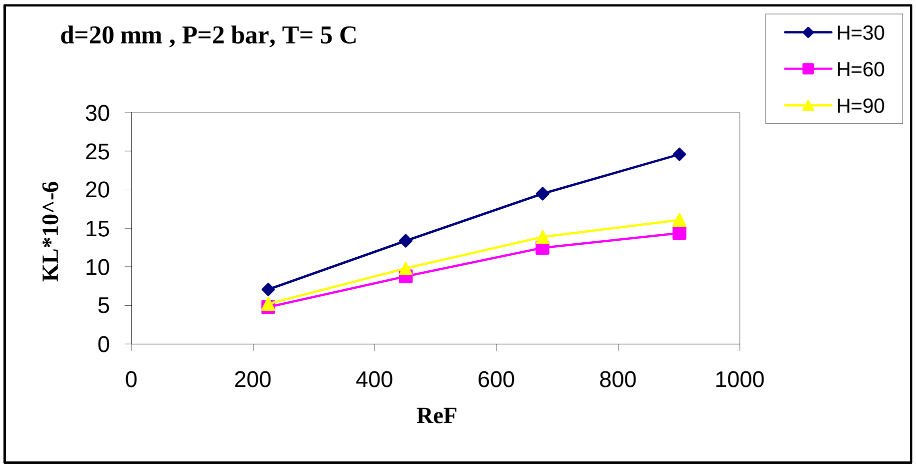


Figure (4.17) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 20 mm , P = 2 bar , T = 5 C).

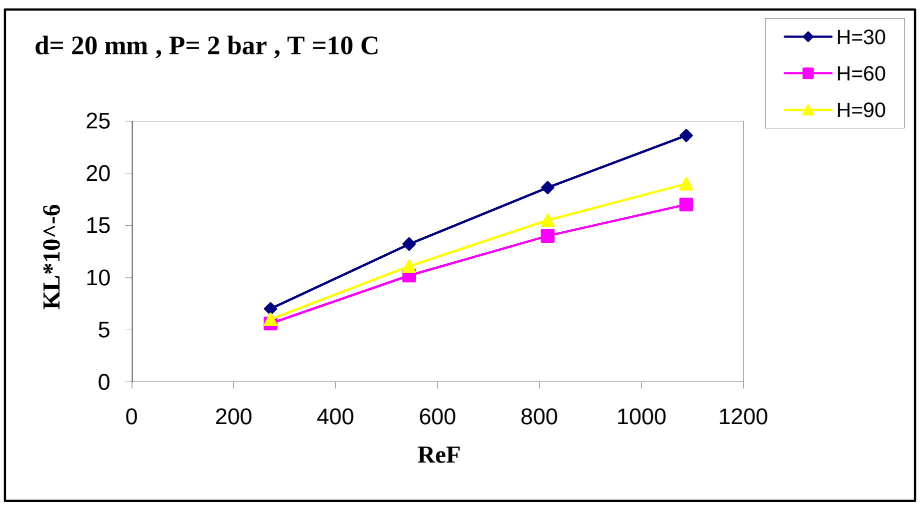


Figure (4.18) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 20 mm , P = 2 bar , T = 10 C).

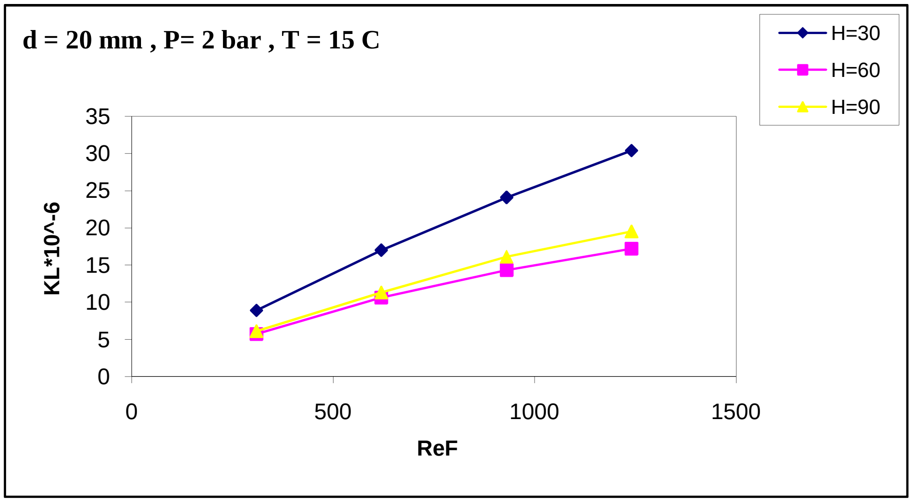


Figure (4.19) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 20 mm , P = 2 bar , T = 15 C).

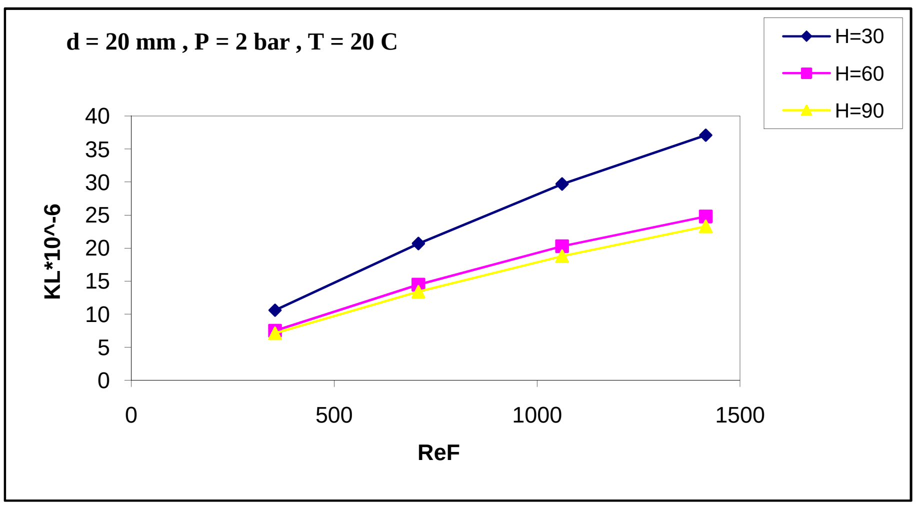


Figure (4.20) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 20 mm , P = 2 bar , T = 20 C).

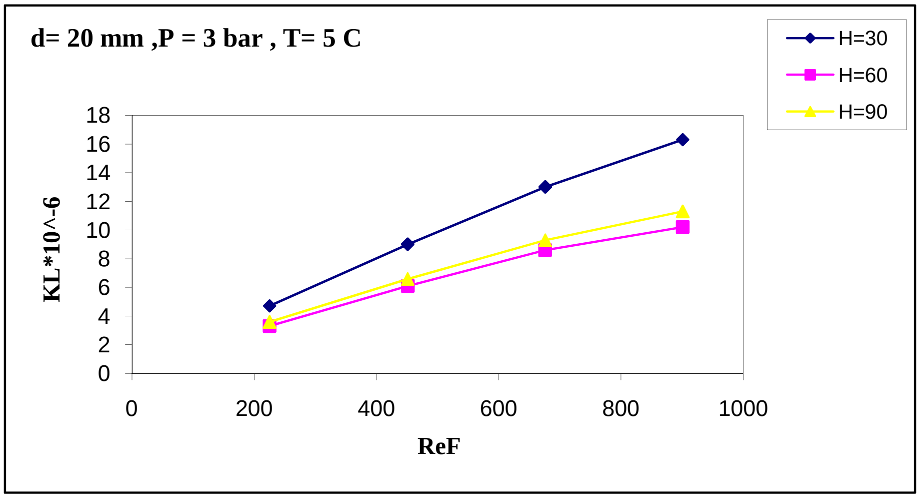


Figure (4.21) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 20 mm , P = 3 bar , T = 5 C).

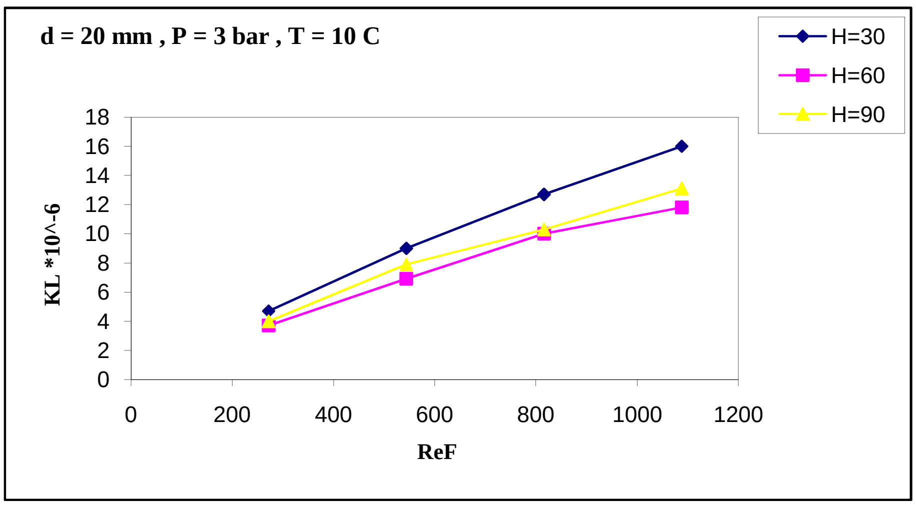


Figure (4.22) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 20 mm , P = 3 bar , T =10 C).

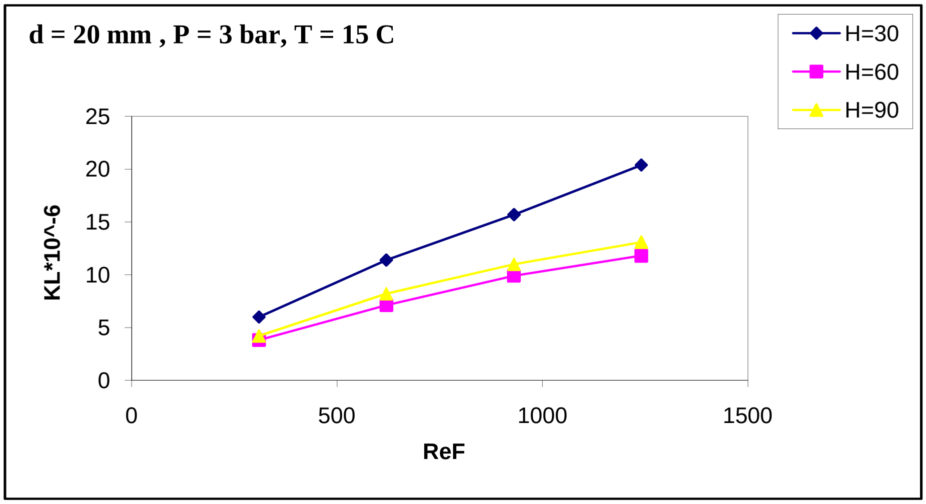


Figure (4.23) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 20 mm , P = 3 bar , T =15 C).

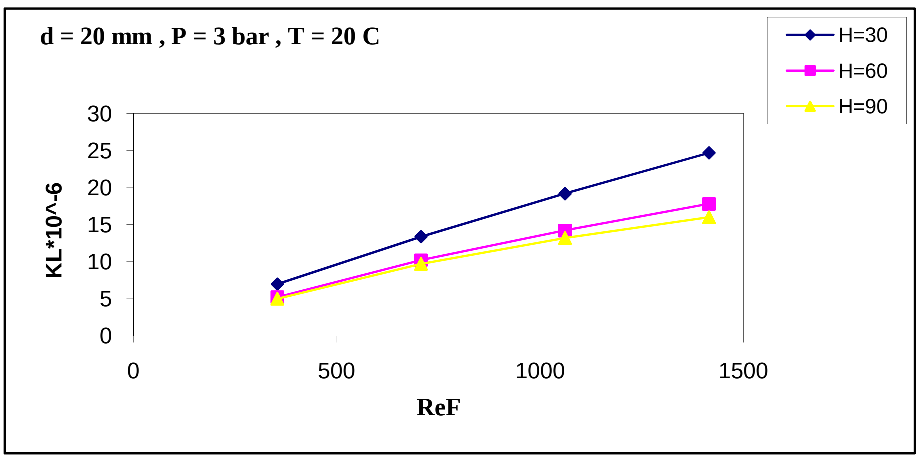


Figure (4.24) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 20 mm , P = 3 bar , T =20 C).

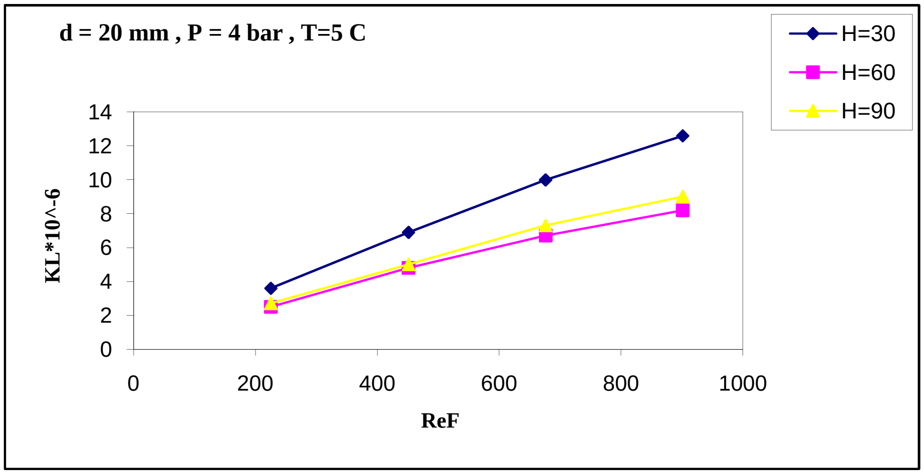


Figure (4.25) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 20 mm , P = 4 bar , T = 5 C).

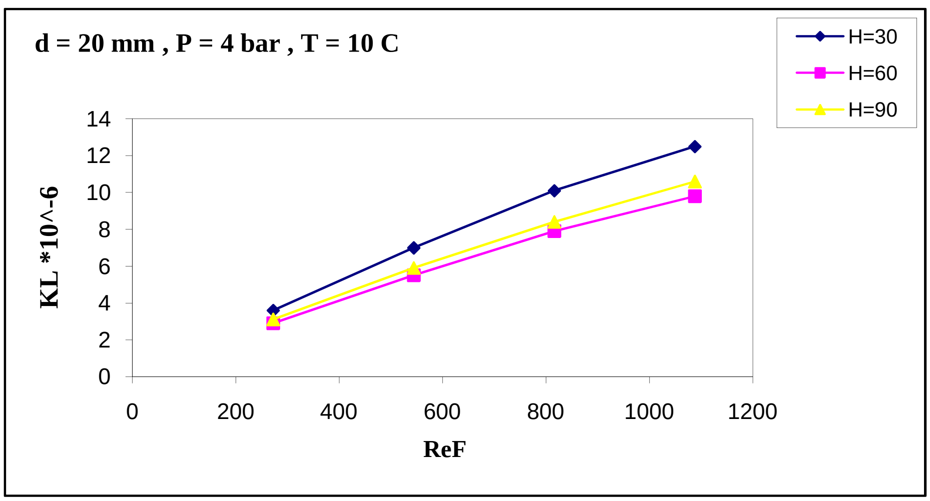


Figure (4.26) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 20 mm , P = 4 bar , T = 10 C).

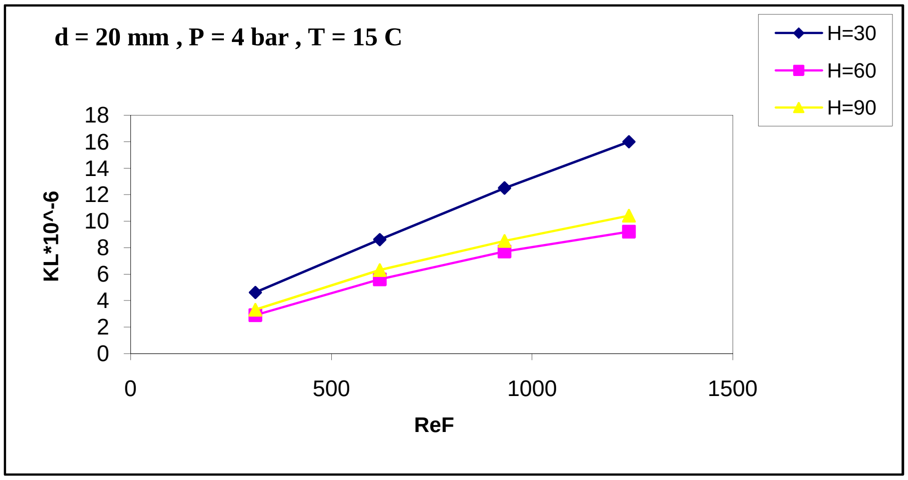


Figure (4.27) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 20 mm , P = 4 bar , T = 15 C).

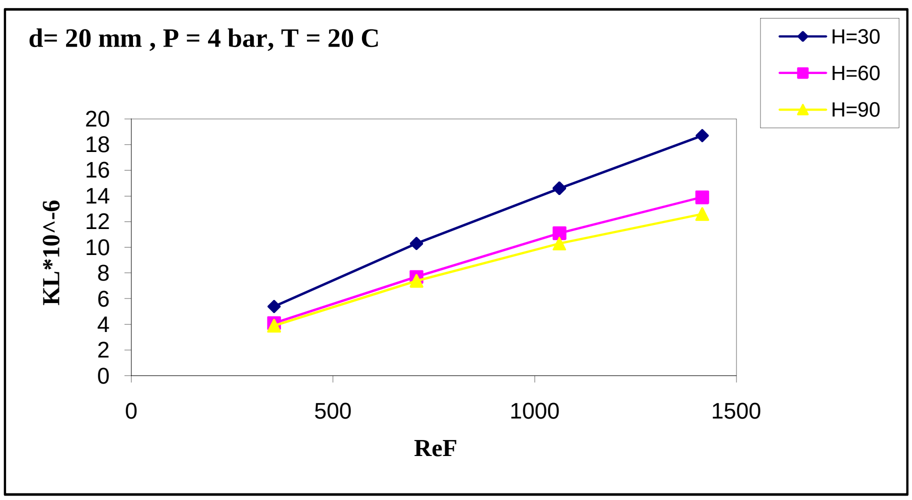


Figure (4.28) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 20 mm , P = 4 bar , T = 20 C).

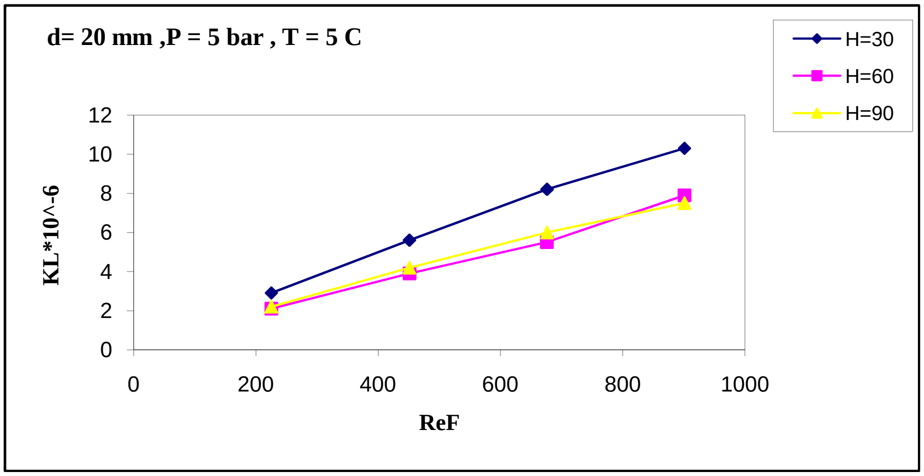


Figure (4. 29) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 20 mm , P = 5 bar , T = 5C).

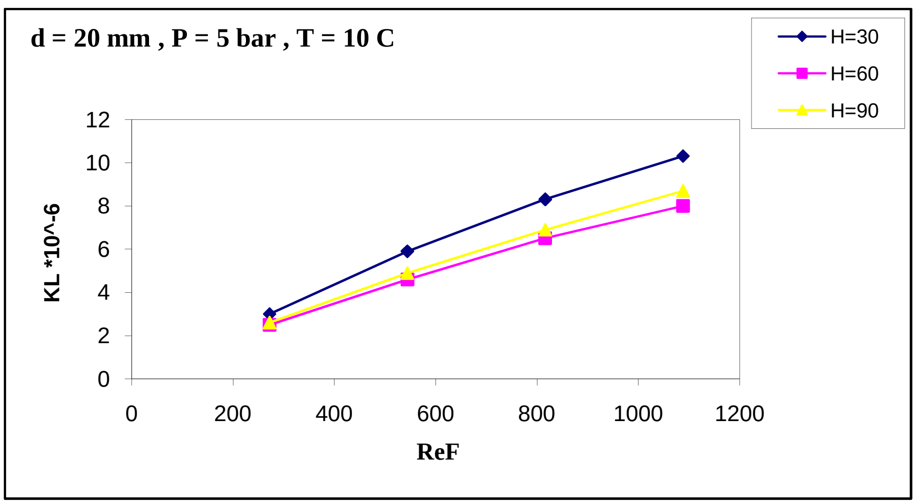


Figure (4.30) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 20 mm , P = 5 bar , T = 10 C).

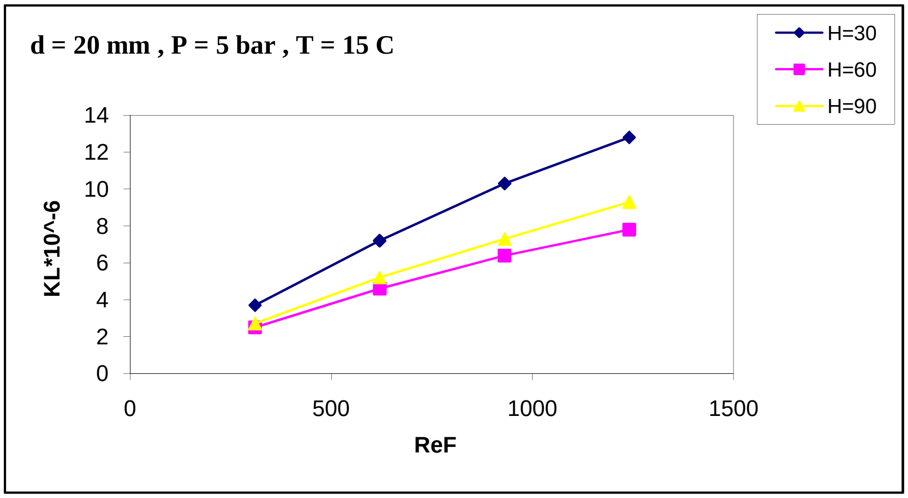


Figure (4.31) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 20 mm , P = 5 bar , T = 15 C).

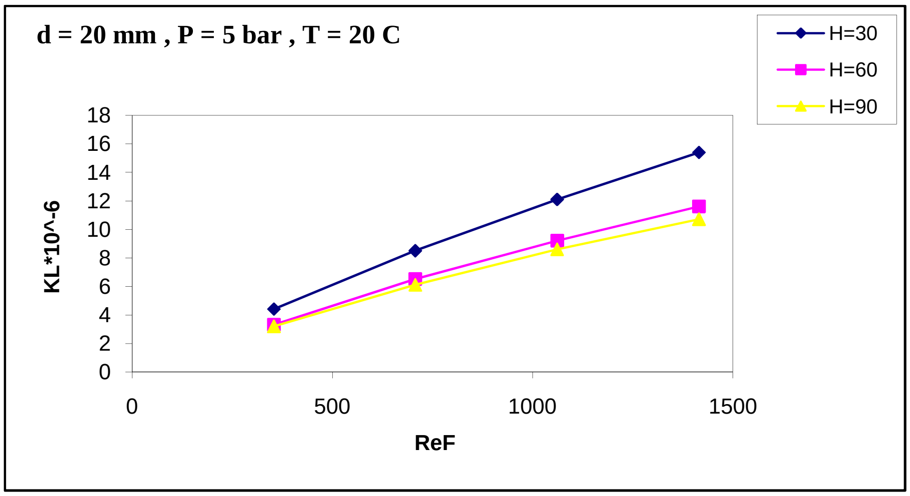


Figure (4.32) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various angle of inclination of the helical coil at (d = 20 mm , P = 5 bar , T = 20 C).

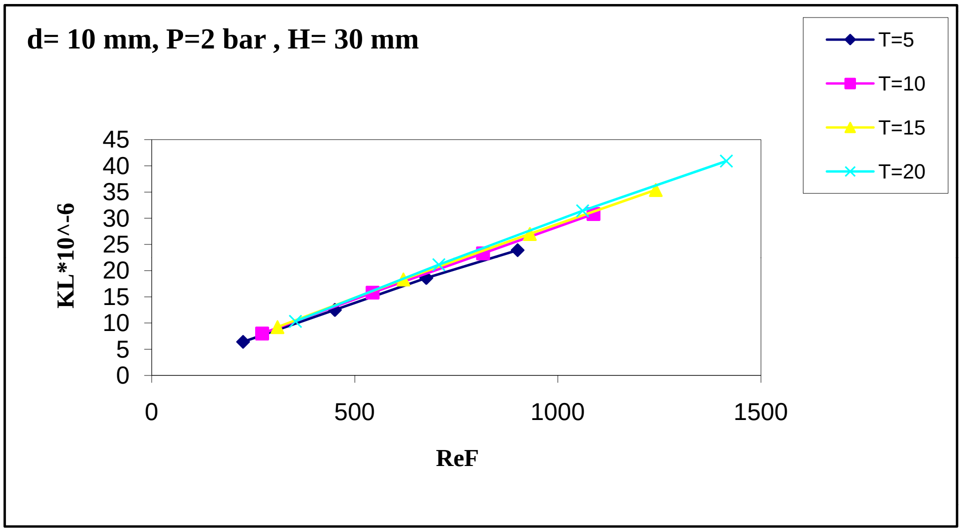


Figure (4.57) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 10 mm , P = 2 bar, H= 30 mm).

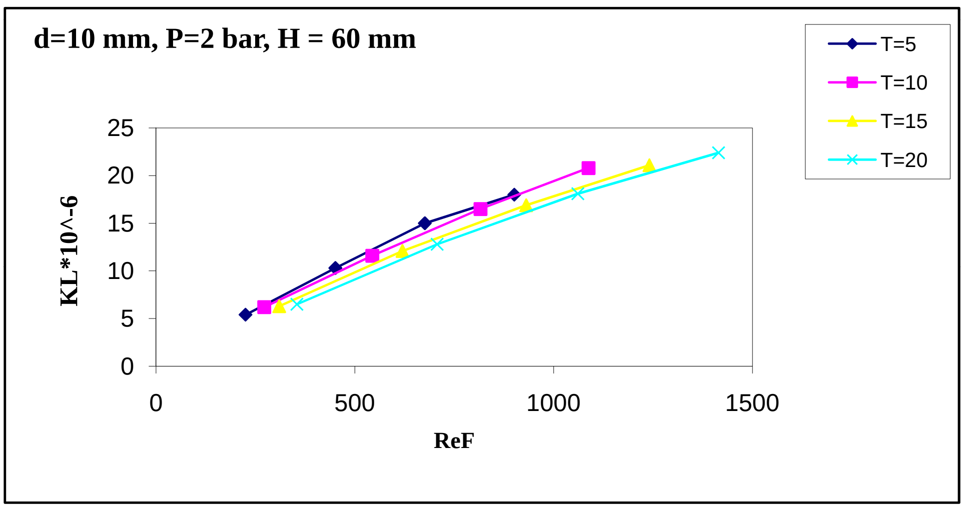


Figure (4.58) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 10 mm , P = 2 bar, H= 60 mm).

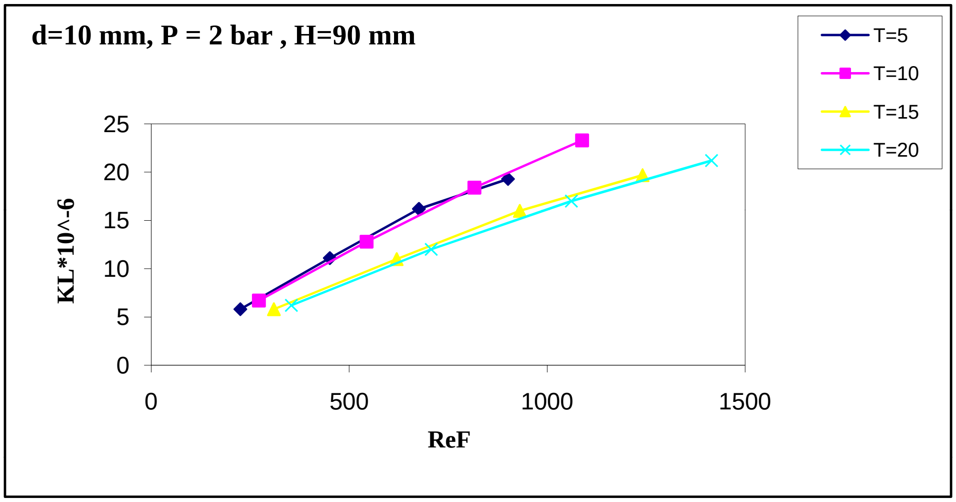


Figure (4.59) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 10 mm , P = 2 bar, H=90 mm).

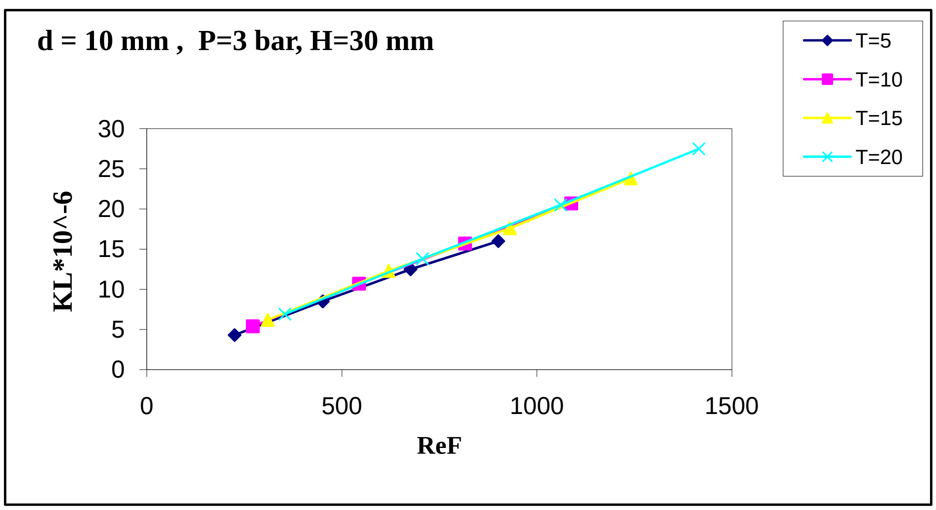


Figure (4.60) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 10 mm , P = 3 bar, H=30 mm).

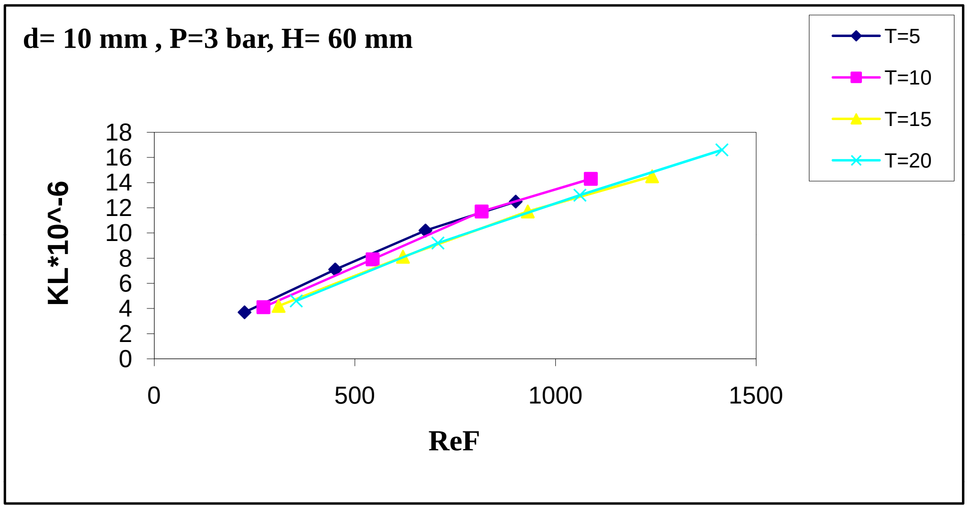


Figure (4-61) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 10 mm , P = 3 bar, H=60 mm).

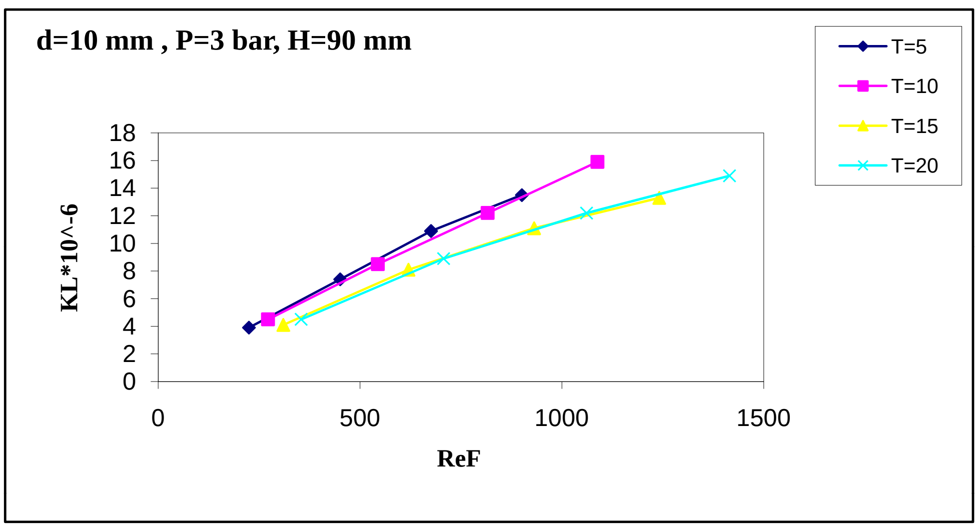


Figure (4-62) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 10 mm , P = 3 bar, H=90 mm).

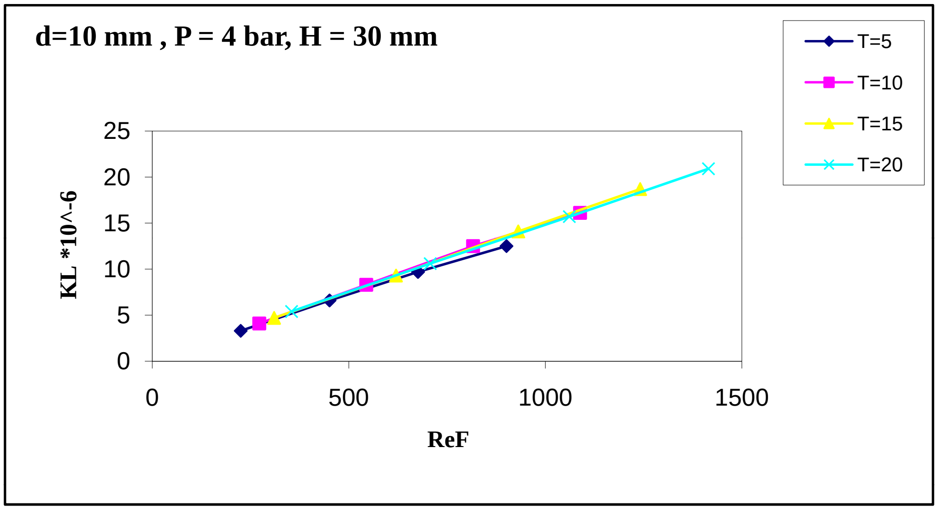


Figure (4-63) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 10 mm , P = 4 bar, H=30 mm).

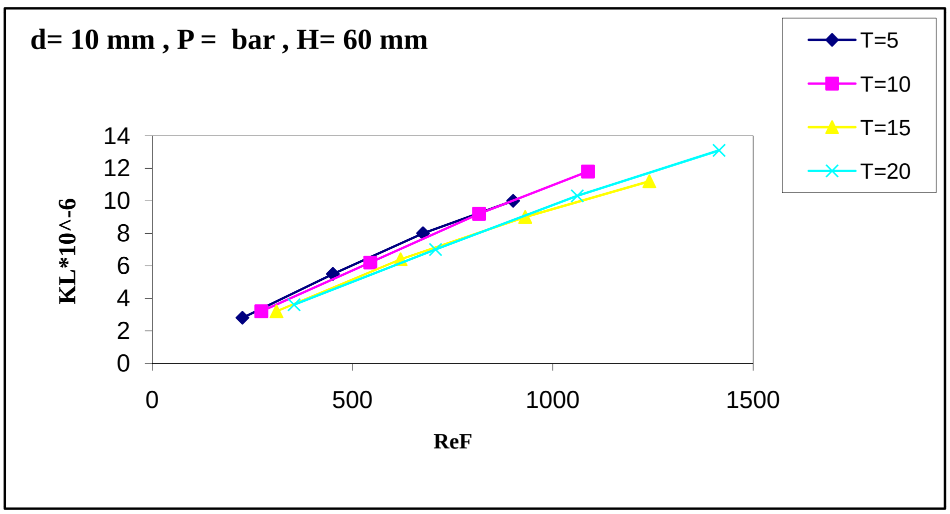


Figure (4.64) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 10 mm , P = 4 bar, H=60 mm).

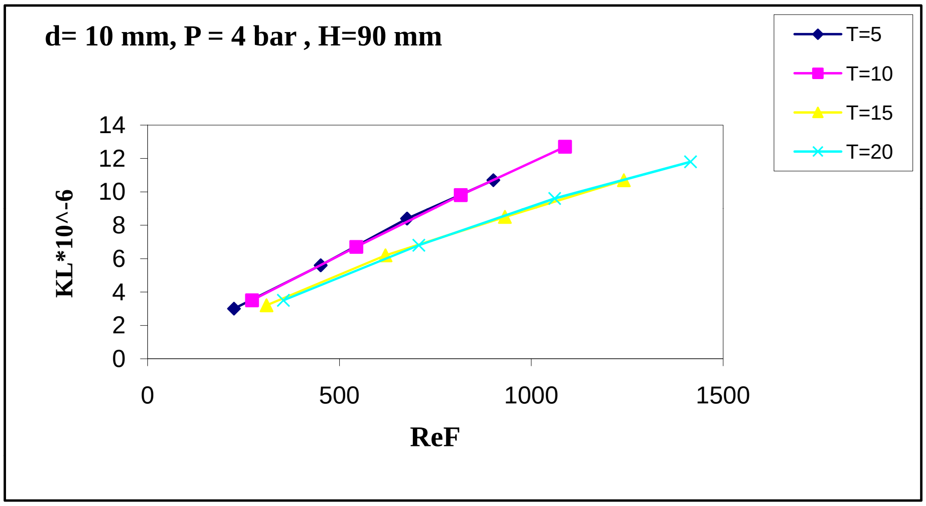


Figure (4.65) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 10 mm , P = 4 bar, H=90 mm).

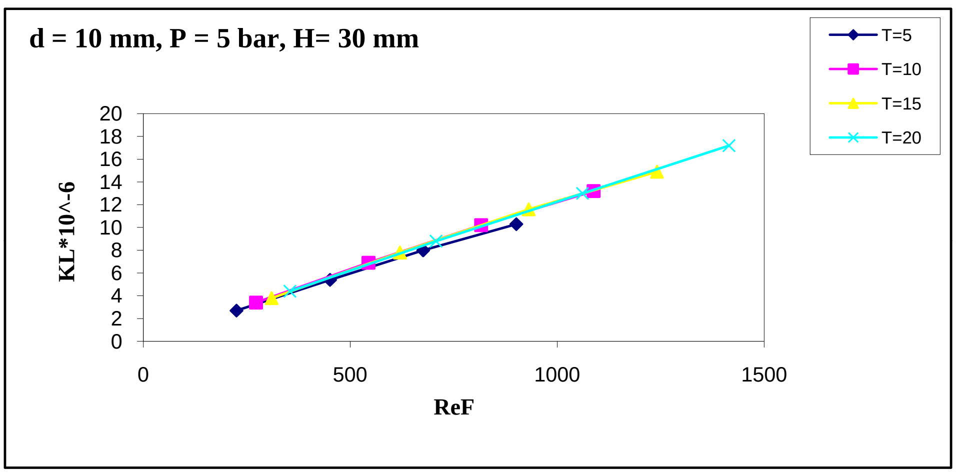


Figure (4-66) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 10 mm , P = 5 bar, H=30 mm).

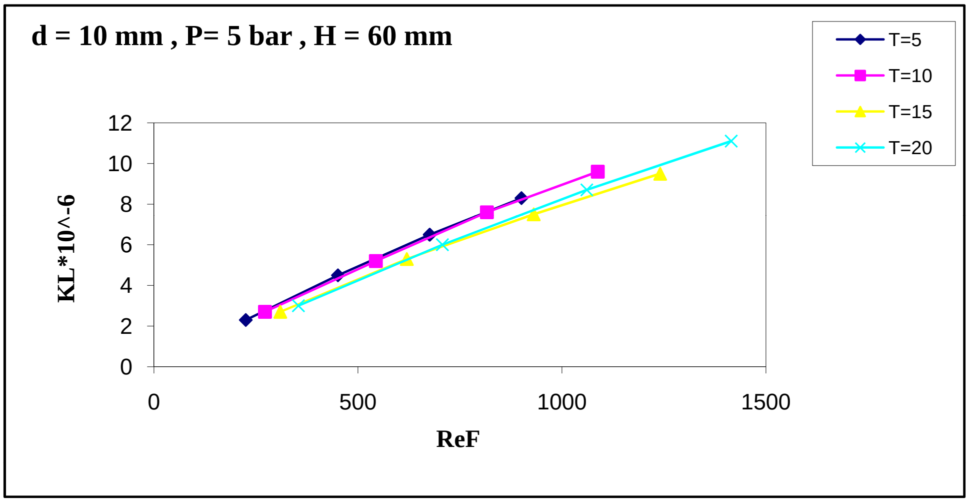


Figure (4.67) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 10 mm , P = 5 bar, H=60 mm).

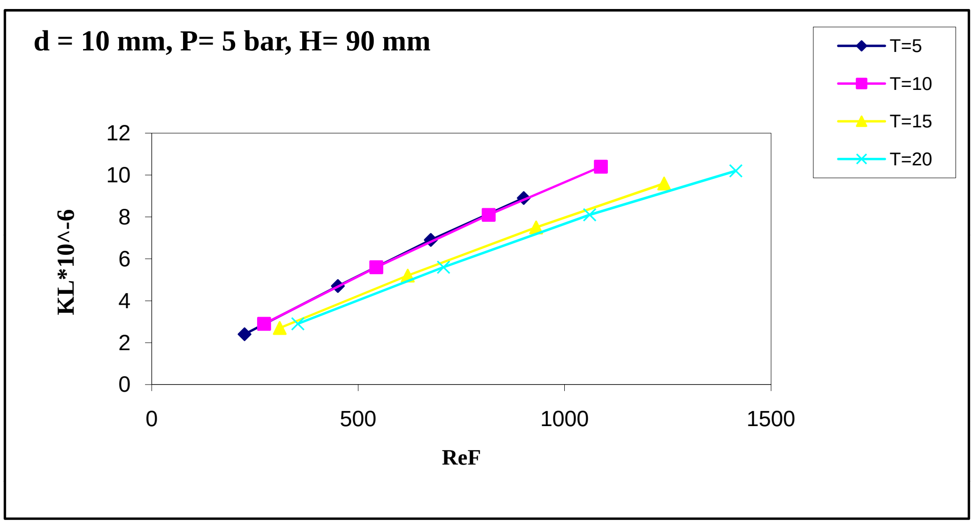


Figure (4.68) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 10 mm , P = 5 bar, H=90 mm).

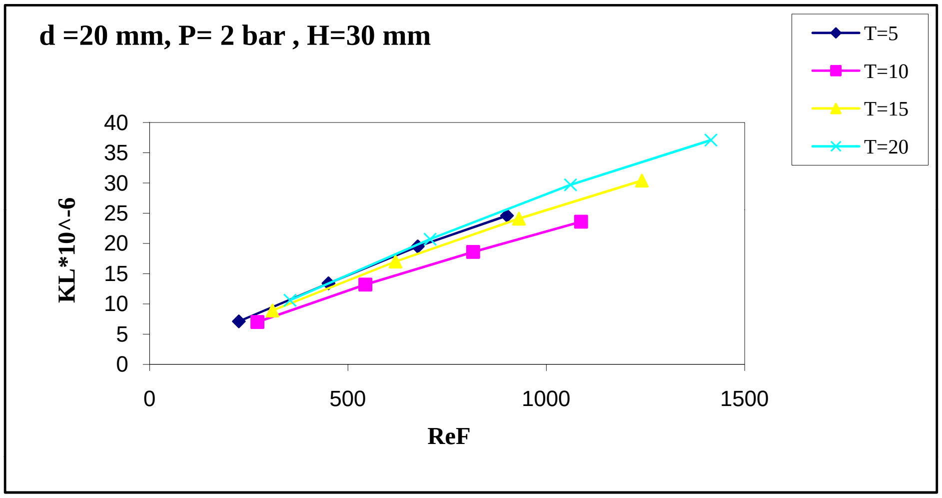


Figure (4.69) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 20 mm , P = 2 bar, H=30 mm).

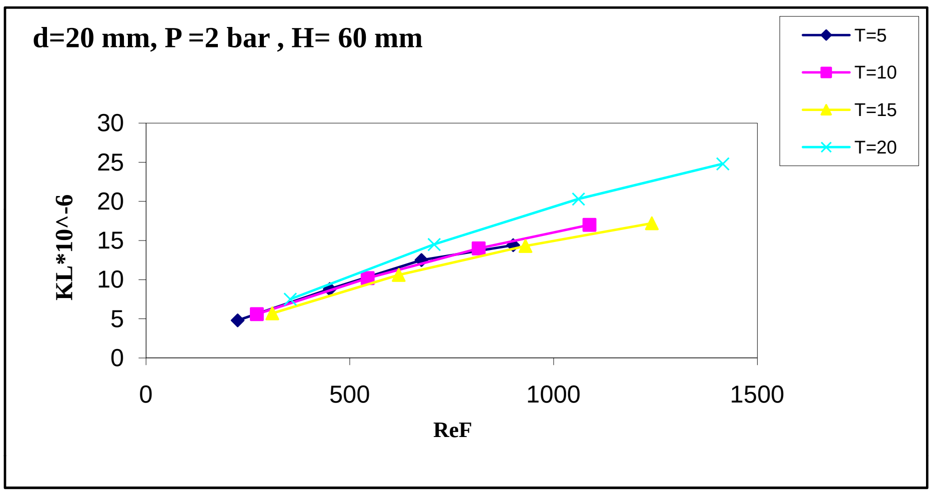


Figure (4.70) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 20 mm , P = 2 bar, H=60 mm).

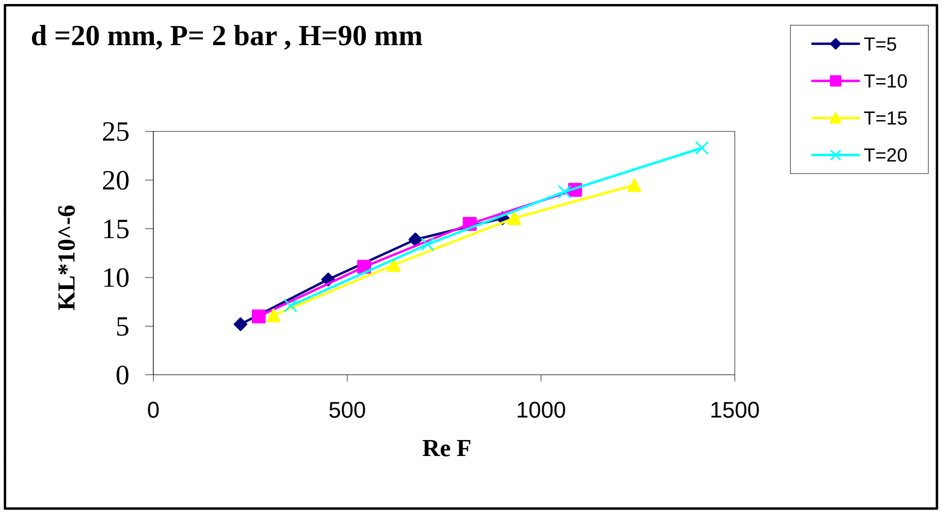


Figure (4.71) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 20 mm , P = 2 bar, H=90 mm).

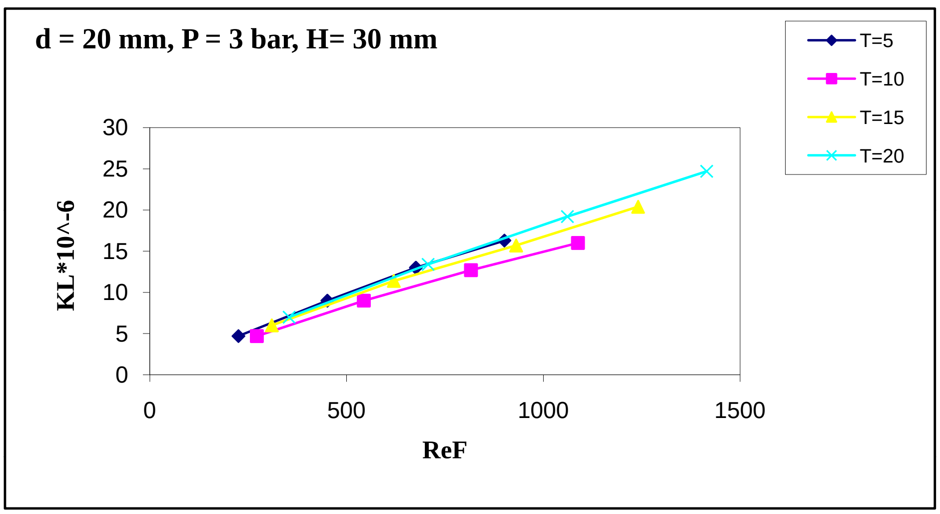


Figure (4.72) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 20 mm , P = 3 bar, H=30 mm).

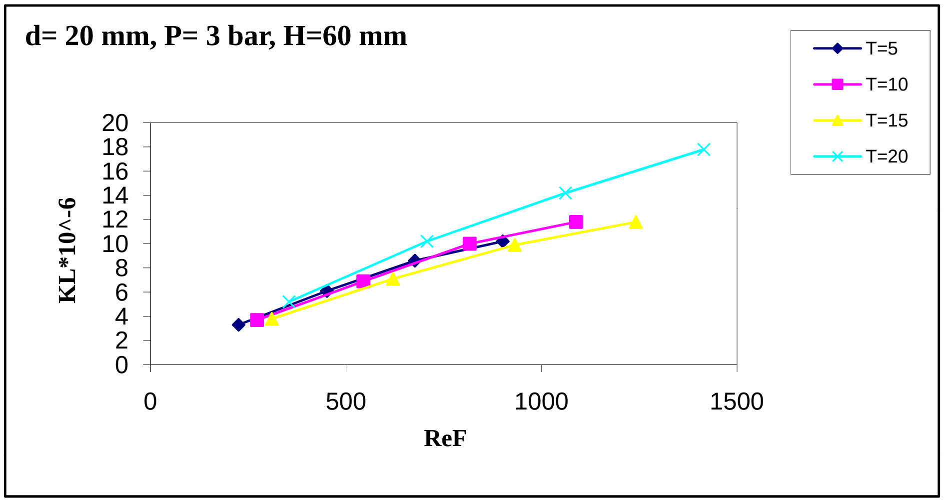


Figure (4.73) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 20 mm , P = 3 bar, H=60 mm).

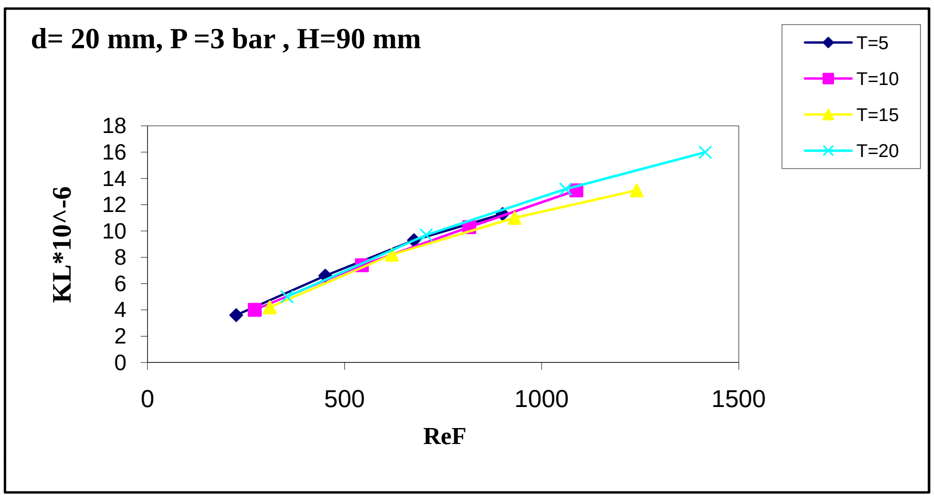


Figure (4.74) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 20 mm , P = 3 bar, H=90 mm).

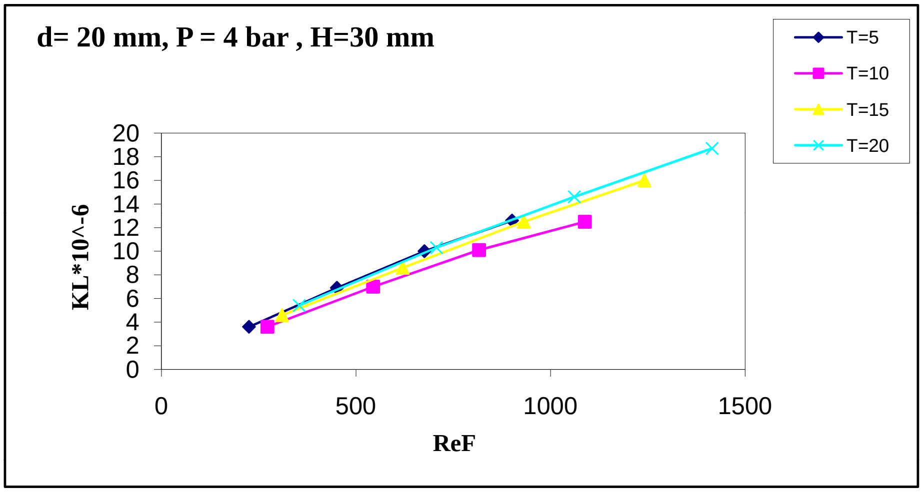


Figure (4.75) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 20 mm , P = 4 bar, H=30 mm).

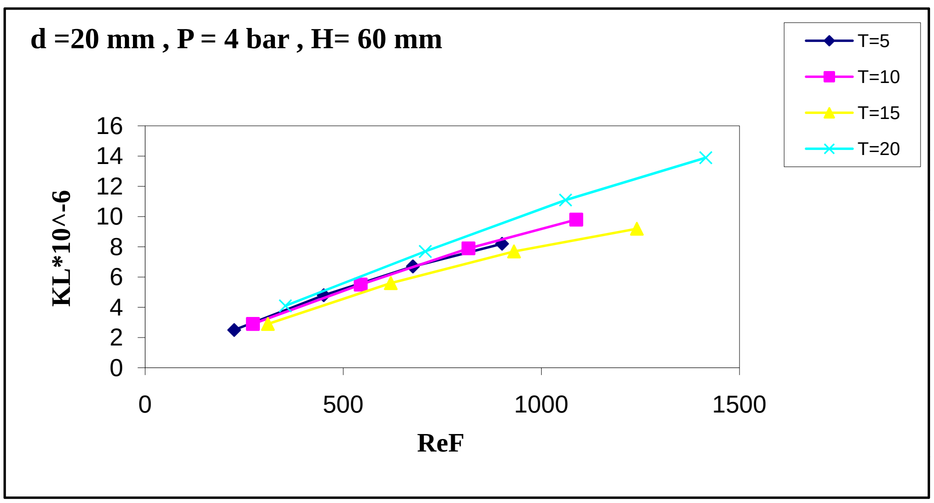


Figure (4.76) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 20 mm , P = 4 bar, H=60 mm).

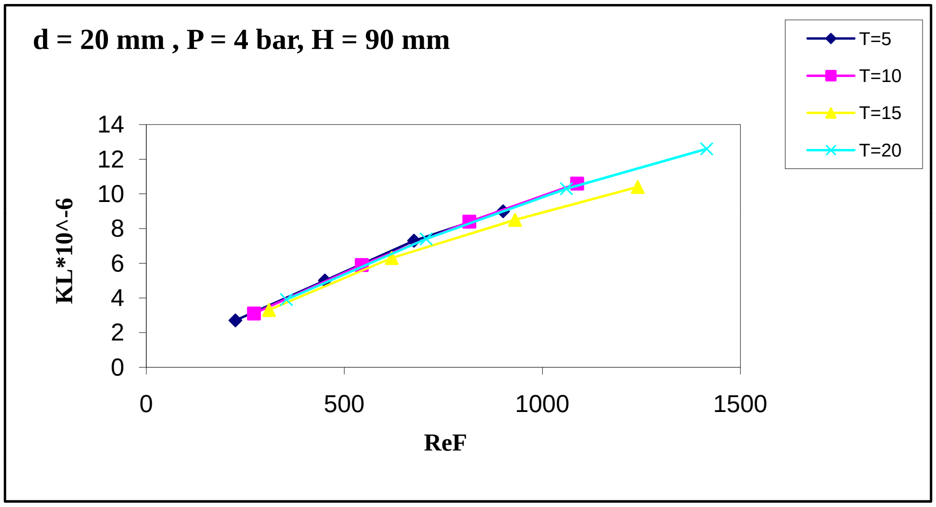


Figure (4.77) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 20 mm , P = 4 bar, H=90 mm).

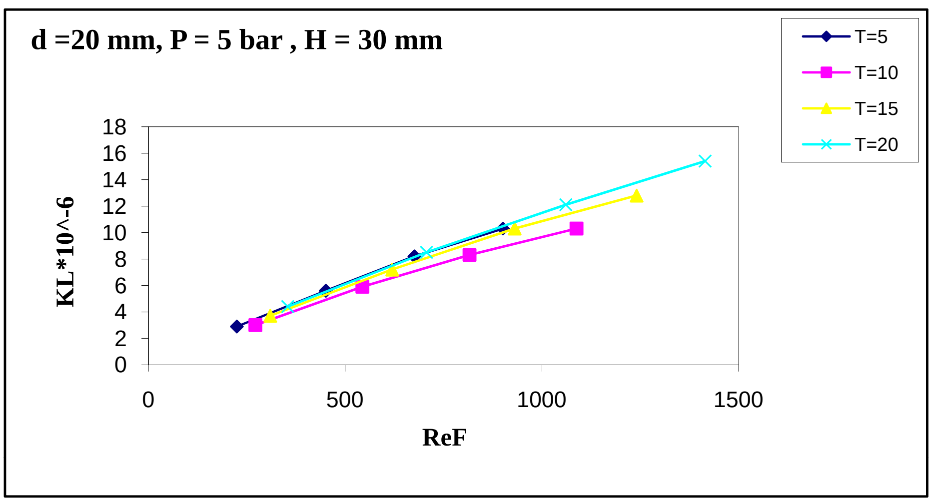


Figure (4.78) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 20 mm , P = 5 bar, H=30 mm).

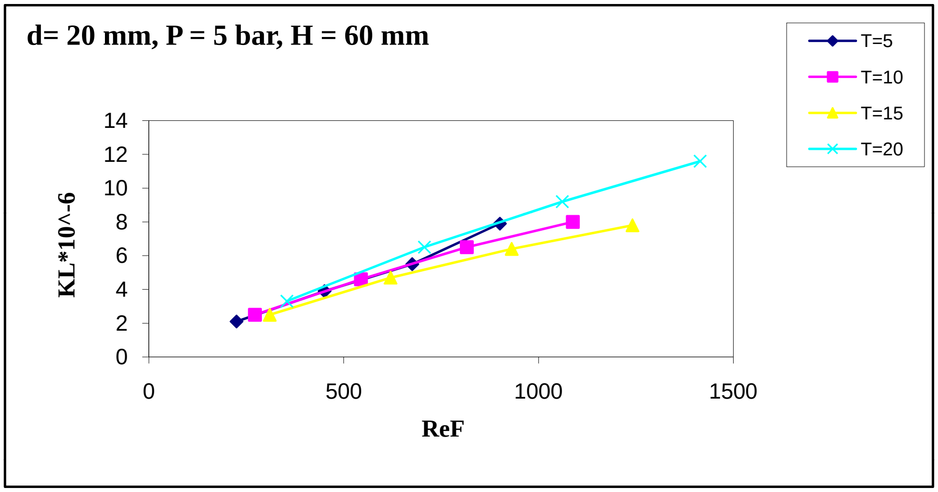


Figure (4.79) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 20 mm , P = 5 bar, H=60 mm).

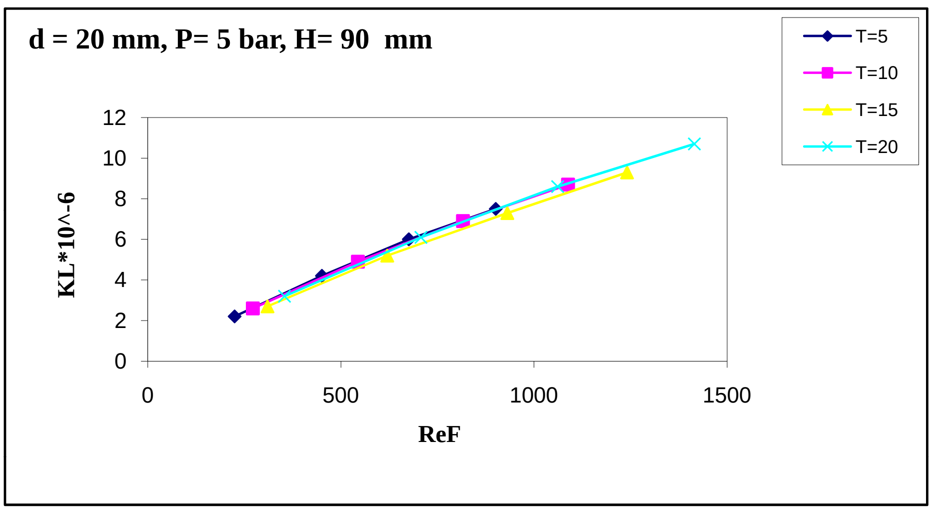


Figure (4.80) The variation of the liquid film mass transfer coefficient versus film Reynolds number at various temperature of the helical coil at (d = 20 mm , P = 5 bar, H=90 mm).

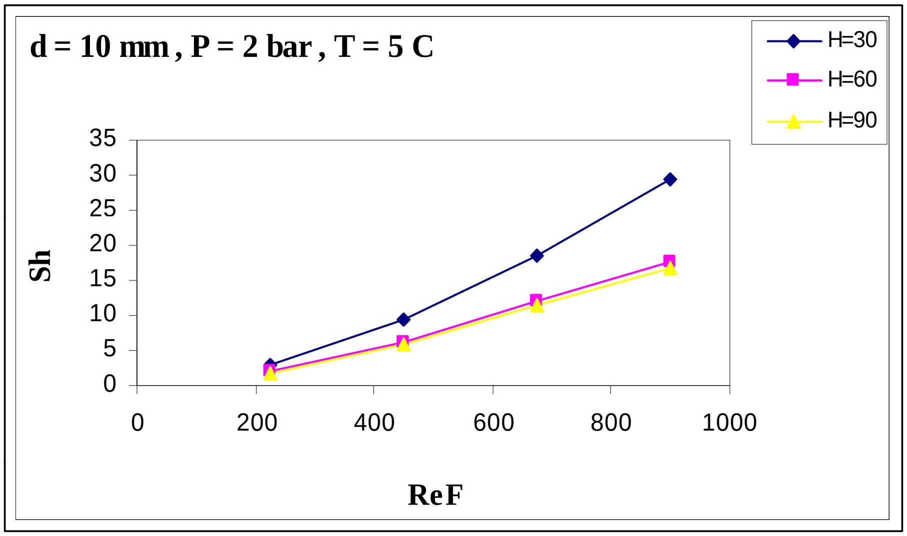


Figure (4.81) The variation of Sherwood number verses Reynolds number at variation angle of inclination (d =10 mm, P =2 bar , T = 5 C).

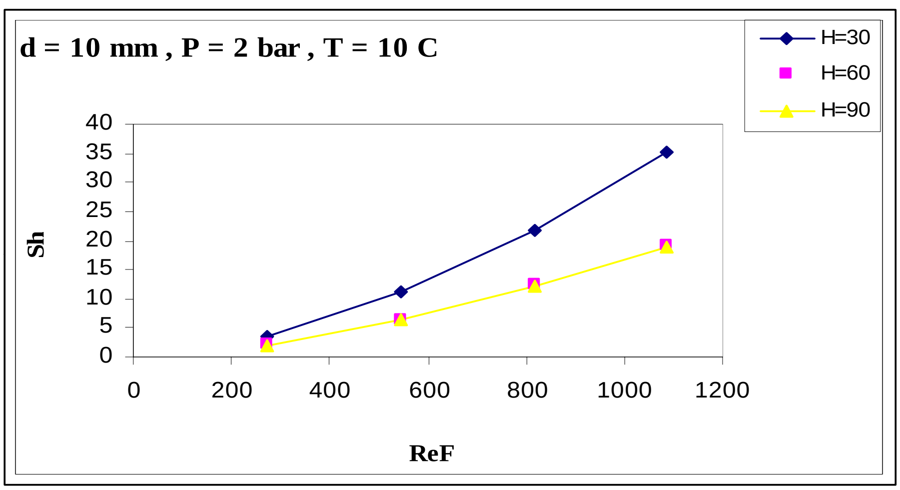


Figure (4.82) The variation of Sherwood number verses Reynolds number at variation angle of inclination (d =10 mm, P =2 bar , T =10 C).

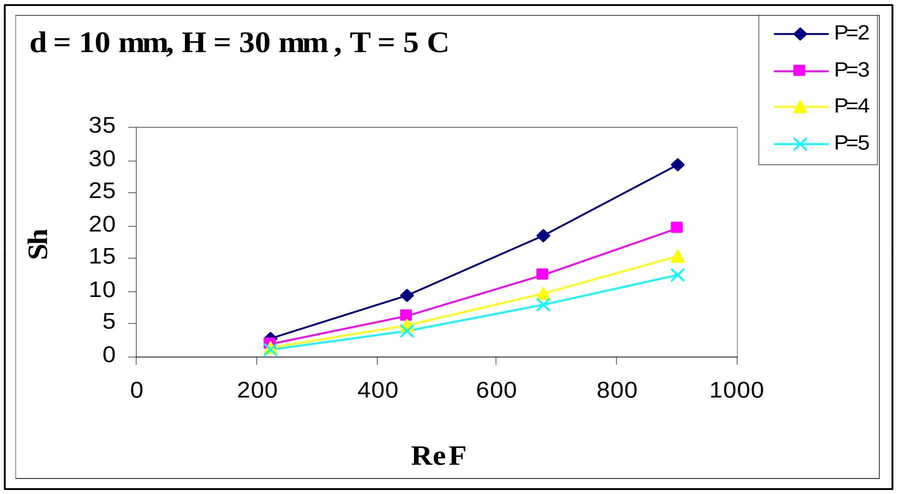


Figure (4.83) The variation of Sherwood number verses Reynolds number at variation system Pressure (d =10 mm, H =30 mm ,T =5 C).

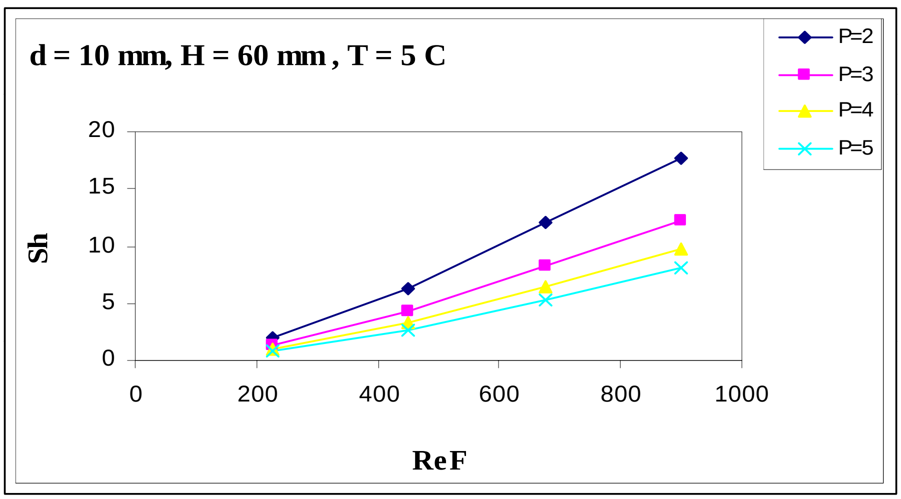


Figure (4.84) The variation of Sherwood number verses Reynolds number at variation system Pressure (d =10 mm, H =60 mm ,T =5 C).

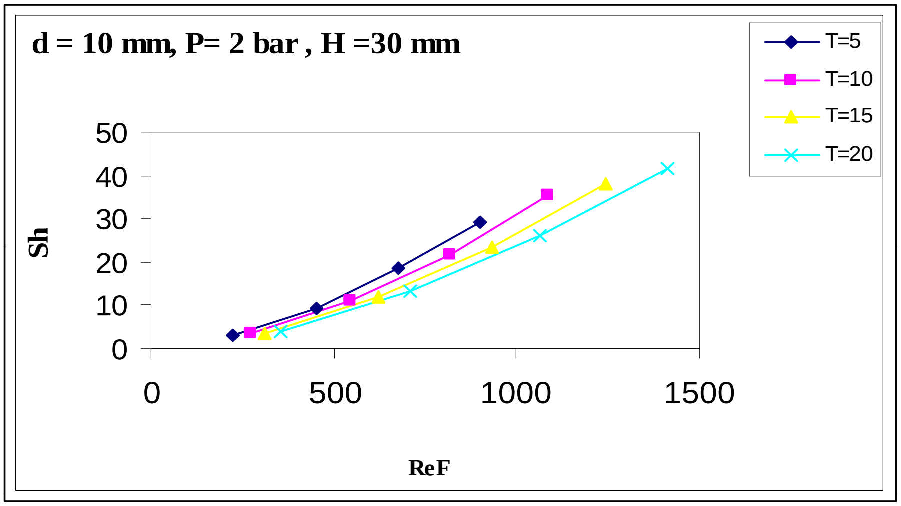


Figure (4.85) The variation of Sherwood number verses Reynolds number at variation temperature (d =10 mm, P = 2 bar,H =30 mm).

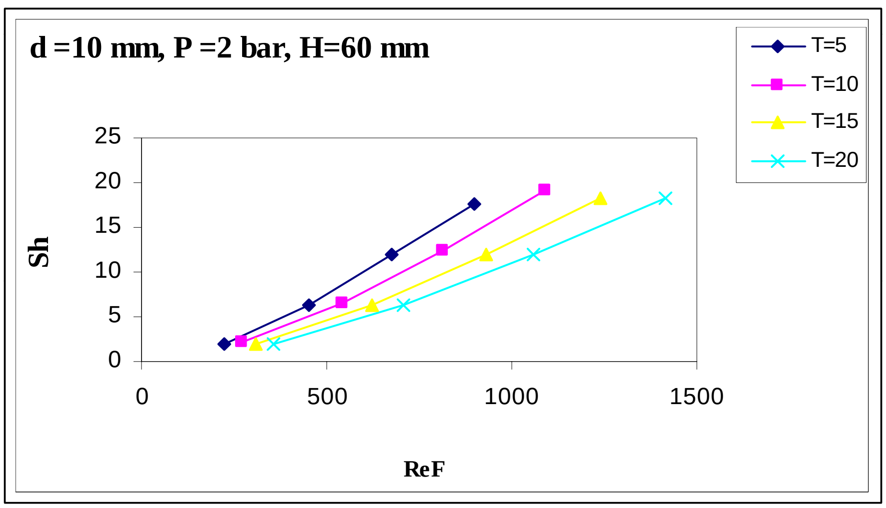


Figure (4.86) The variation of Sherwood number verses Reynolds number at variation temperature (d =10 mm, P = 2 bar,H =60 mm).

4.5 Correlation Of The Experimental Data

Empirical correlation, to predict the liquid film mass transfer coefficient K_L , is derived using dimensional analysis to give the following form:-

$$Sh = 1.484 *10^{-6} \; Re_F^{\,1.52} \; Sc^{\,0.623} \; \sin\theta^{\,-0.606} \qquad \ldots (4.1)$$

LINEST function of Microsoft Excel program was used for the 384 experimental data points , giving the correlation coefficient $R^2 = 0.870$.

The validity of using Equation (4 . 1) to predict the liquid film mass transfer coefficient or Sherwood number is shown in Figure (4 .88). The experimental data are within ± 30 % of the calculated values.

There is no parameter in the right hand side of Eq.(4 . 1) account for the system pressure of CO_2 gas (P) effect on the dependent variable K_L or Sh. The following equations were derived at different system pressure of CO_2 gas :-

P = 2 bar

$$Sh = 2.236 *10^{-6} \; Re_F^{\,1.51} \; Sc^{\,0.643} \; \sin\theta^{\,-0.635} \qquad \ldots (4.2)$$

$R^2 = 0.9818$

P = 3 bar

$$Sh = 1.799 *10^{-6} \; Re_F^{\,1.51} \; Sc^{\,0.608} \; \sin\theta^{\,-0.613} \qquad \ldots (4.3)$$

$R^2 = 0.9844$

P = 4 bar

$$Sh = 1.154 *10^{-6} \; Re_F^{\,1.53} \; Sc^{\,0.595} \; \sin\theta^{\,-0.628} \qquad \ldots (4.4)$$

$R^2 = 0.9856$

P = 5 bar

$$Sh = 1.044 * 10^{-6} \ Re_F^{1.53} \ Sc^{-0.578} \ \sin\theta^{-0.615} \qquad \ldots(4.5)$$

$R^2 = 0.9870$

The validity of using Equations (4 .2) to (4 . 5) to correct the liquid film mass transfer coefficient or Sherwood number is shown in Figures (4. 89) to (4 .92).The experimental data are within ± 10 % of the calculated values.

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

$$Sh = 4.314 * 10^{-6} \ Re_F^{1.52} \ Sc^{0.623} \ \sin\theta^{0.606} \ P^{-0.8918} \qquad \ldots(4.6)$$

With $R^2 = 0.9862$

The experimental data are within ± 10 % of the calculated values, as shown in Fig. (4.93)

4.6 Comparison with previous work

Jawad [2] did not study the effect of the system variables on the mass transfer coefficient (K_L). He studied effect of the system variables on mass transfer rate represented as absorption of CO_2 take – up.

Table (4.1) Show a comparison of the values of the parameters of the empirical equation descriping the system with previous work.

Table (4.1) Comparison of the values of the parameters of the empirical equation descriping the system with previous work.

Flow	Value of parameters				Ref.
	ReF	Sc	P	Sin θ	
Wavy laminar	1.52	0.62	-0.89	0.6	Present work
Laminar	1.13	0.73	_	0.5	[3,4]
Turbulent	1.4	0.54	_	0.45	
Turbulent	1.5	0.5	_	_	[49]
Laminar	1	-0.5	_	_	[50]

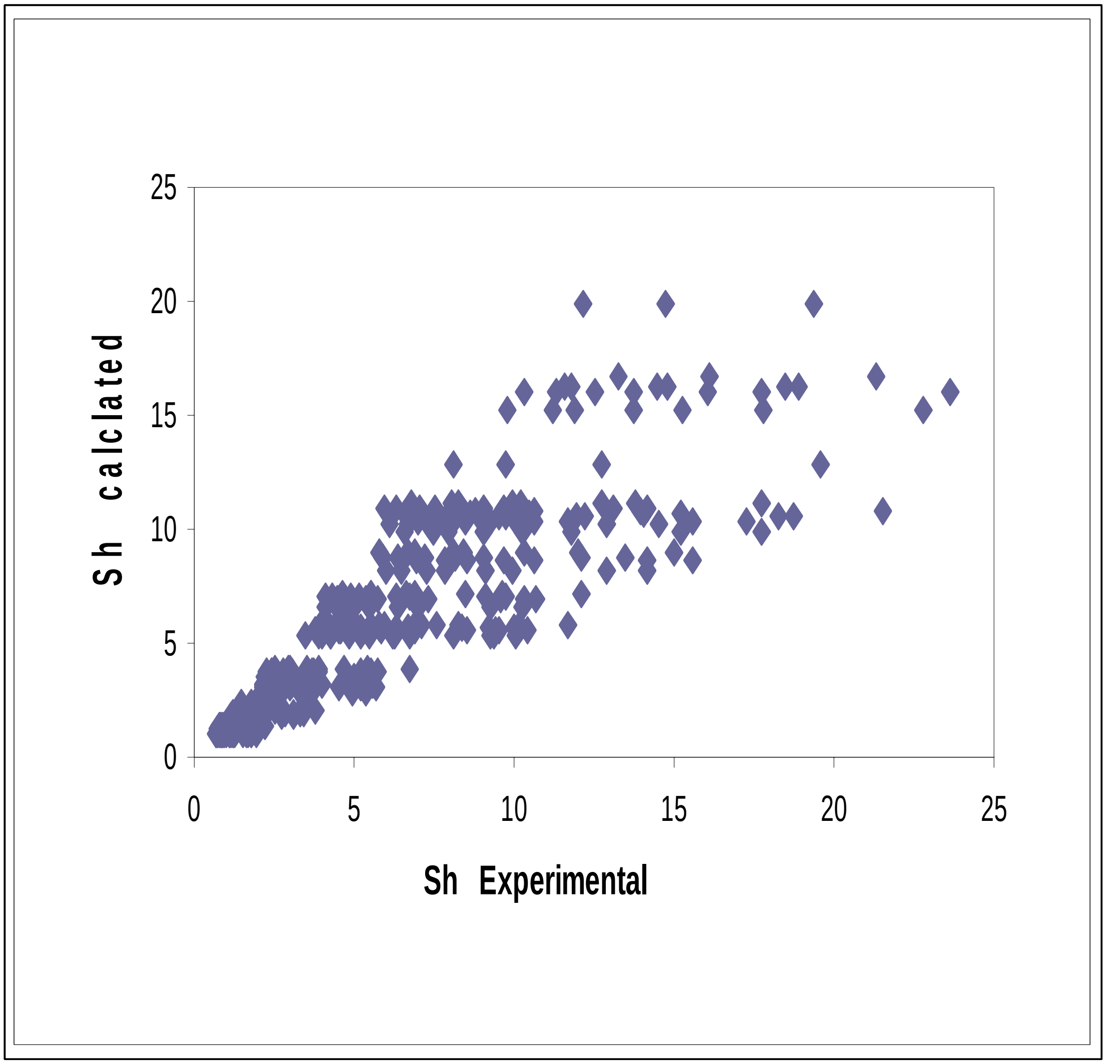


Figure (4.88) Comparison of experimental data calculated from eqation (4.1) Sherwood number for film in helical tubes

$$Sh = 1.484 * 10^{-6} \; Re_F^{\,1.52} \; Sc^{\,0.623} \; Sin\theta^{\,-0.606} \qquad \ldots (4.1)$$

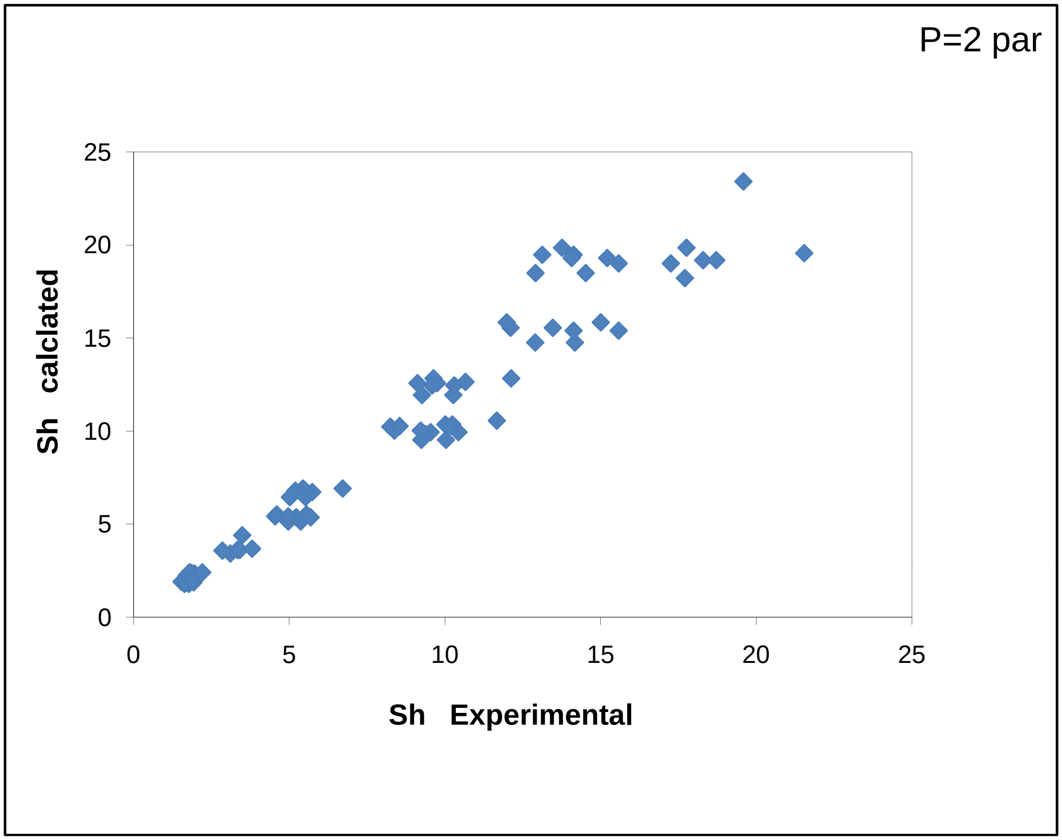


Figure (4.89) Comparison of experimental and calculated Sherwood number for film helical tubes at P = 2 bar for eqation (4.2).

$$Sh = 2.236 * 10^{-6} \quad Re_F^{\ 1.51} \quad Sc^{\ 0.643} \quad Sin\theta^{\ -0.635} \qquad \ldots(4.2)$$

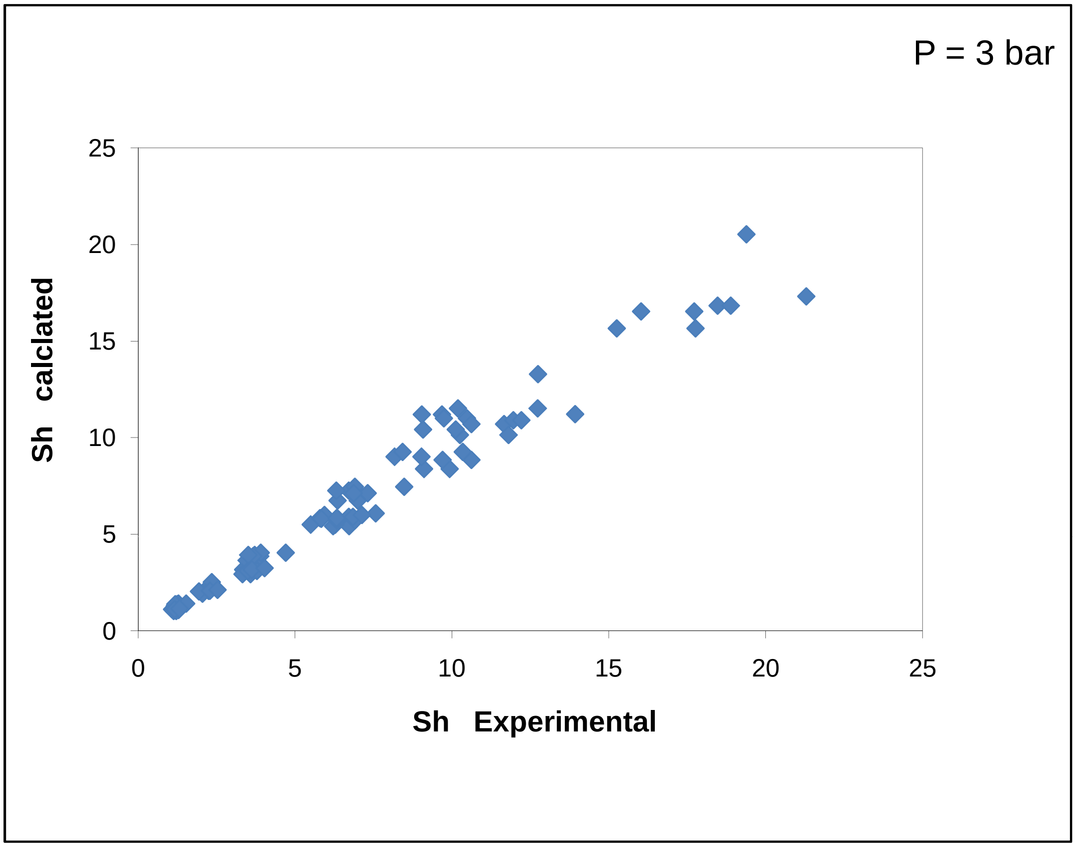


Figure (4.90) Comparison of experimental and calculated Sherwood number for film helical tubes at P = 3 bar for eqation (4.3).

$$Sh = 1.799 * 10^{-6} \; Re_F^{\,1.51} \; Sc^{\,0.608} \; Sin\theta^{\,-0.613} \qquad \ldots(4.3)$$

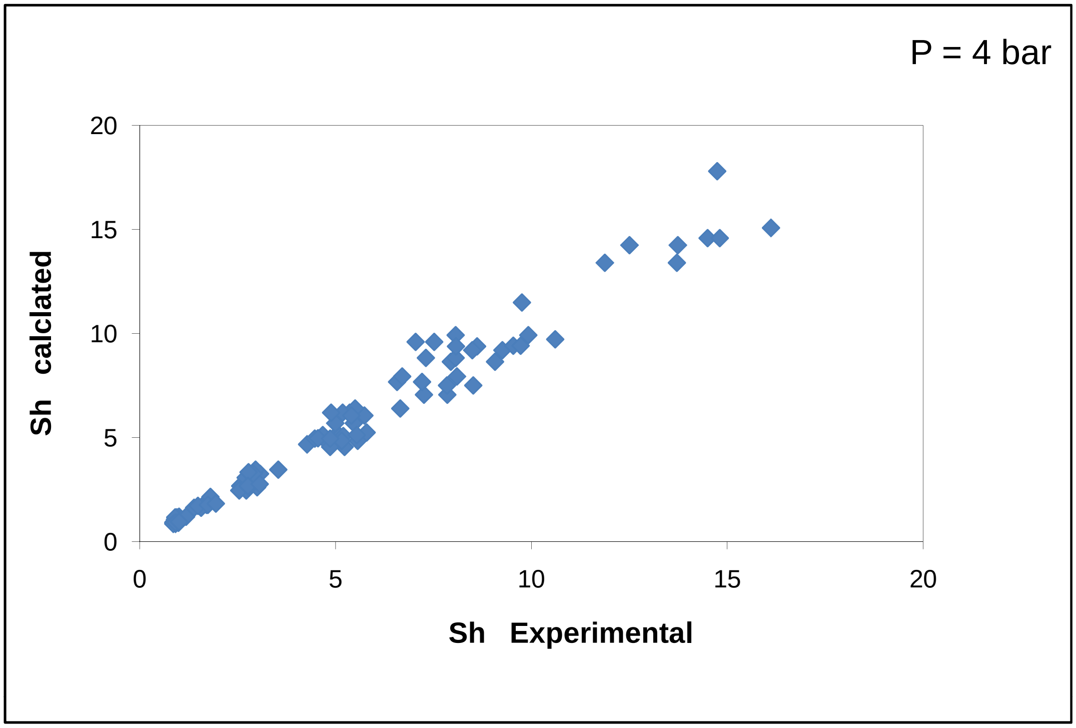


Figure (4.91) Comparison of experimental and calculated Sherwood number for film helical tubes at P = 4 bar for eqation (4.4).

$$Sh = 1.154 * 10^{-6} \; Re_F^{\,1.53} \; Sc^{\,0.595} \; Sin\theta^{\,-0.628} \qquad \ldots(4.4)$$

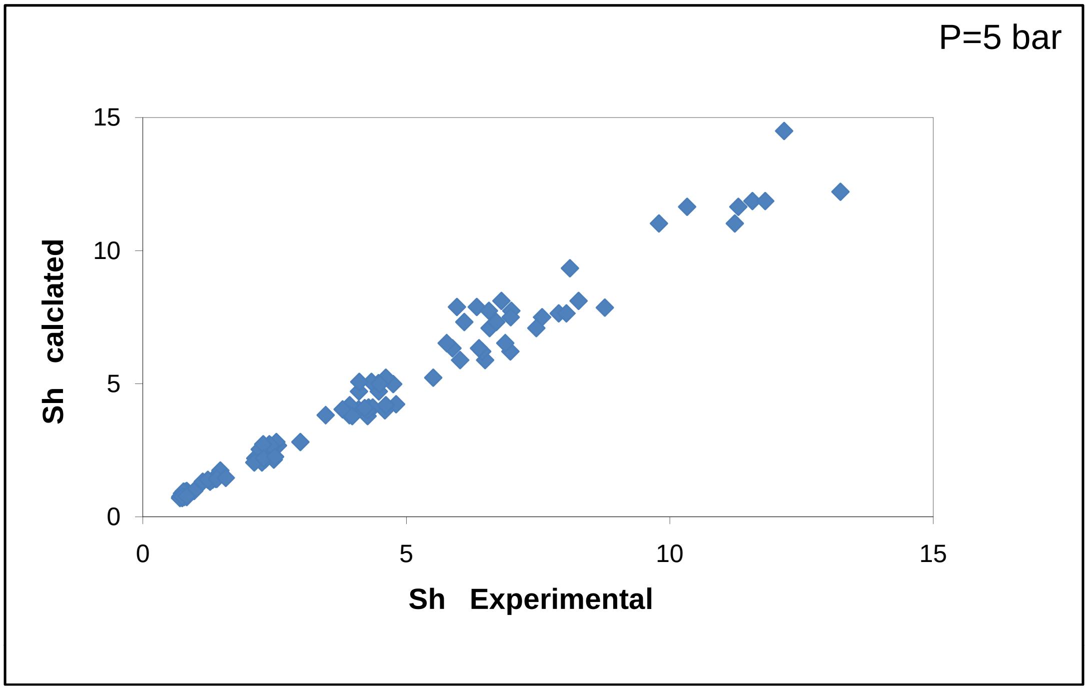


Figure (4.92) Comparison of experimental and calculated Sherwood number for film helical tubes at P = 5 bar for eqation (4.5).

$$Sh = 1.044 * 10^{-6} \ Re_F^{\ 1.53} \ Sc^{\ -0.578} \ Sin \ \theta^{\ -0.615} \qquad \ldots(4.5)$$

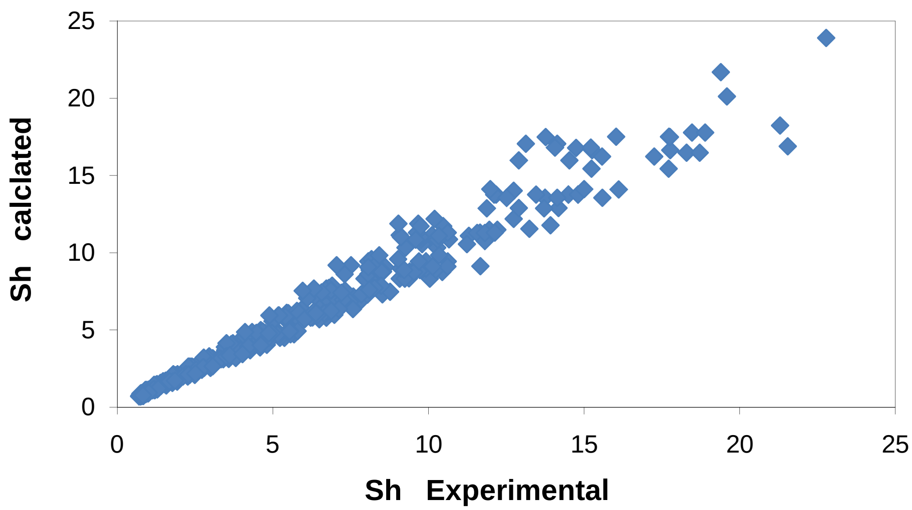


Figure (4.93) Comparison of experimental and calculated Sherwood number for film helical tubes for overall pressure eqation (4.6).

$$Sh = 4.314 * 10^{-6}\ Re_F^{\ 1.52}\ Sc^{\ 0.623}\ \sin\theta^{\ 0.606}\ P^{\ -0.8918} \qquad ... (4.6)$$

CONCLUSIONS

The following conclusions have been drawn from the present work:

1. The film mass transfer coefficient (K_L) increases with increasing film Reynolds number (Re_F), without critical Reynolds number distinguish between laminar and turbulent (up to Re_F =400).
2. The film mass transfer coefficient (K_L) decreases with increasing pitch between two turns (H) or increasing the angle of inclination (θ).
3. The film mass transfer coefficient (K_L) decreases with increasing the pressure of CO_2 gas (P).
4. The film mass transfer coefficient (K_L) was found to be independent of the temperature of the system .
5. Empirical correlation to predict the liquid film mass transfer coefficient (K_L) represented by Sherwood number is derived by using dimensional 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.

6 - The following equations were derived at different system pressure of CO_2 gas with ± 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

7 – Overall correlation for the effect of pressure was given by :-

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

With $R^2 = 0.9862$

Recommendations

1 – Studying the mass transfer with chemical reaction in spiral tubes .

2 – Studying the development of heat transfer in spiral tubes for different range.

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Table (A - 1)Experimental data at (T =5 °C, d= 10 mm, H =30 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (Bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_2 mol/liter	C_3 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
1	10	30	8.5	2	10	25	30	12.3	0.08	0.1	0.0234	0.1288	225	6.4	1733	0.42	2.965
2	10	30	8.5	2	20	25	30	13.2	0.08	0.1	0.0216	0.1288	451	12.5	1733	0.68	9.4
3	10	30	8.5	2	30	25	30	13.8	0.08	0.1	0.0204	0.1288	676	18.6	1733	0.91	18.61
4	10	30	8.5	2	40	25	30	14.6	0.08	0.1	0.0188	0.1288	901	23.9	1733	1.11	29.28
5	10	30	8.5	3	10	25	30	11.9	0.08	0.1	0.0242	0.1934	225	4.3	1733	0.42	1.977
6	10	30	8.5	3	20	25	30	12.7	0.08	0.1	0.0226	0.1934	451	8.5	1733	0.68	6.363
7	10	30	8.5	3	30	25	30	13.4	0.08	0.1	0.0212	0.1934	676	12.5	1733	0.91	12.53
8	10	30	8.5	3	40	25	30	14.3	0.08	0.1	0.0194	0.1934	901	16.0	1733	1.11	19.61
9	10	30	8.5	4	10	25	30	11.4	0.08	0.1	0.0252	0.2582	225	3.3	1733	0.42	1.519
10	10	30	8.5	4	20	25	30	12.1	0.08	0.1	0.0238	0.2582	451	6.6	1733	0.68	4.952
11	10	30	8.5	4	30	25	30	12.9	0.08	0.1	0.0222	0.2582	676	9.7	1733	0.91	9.702
12	10	30	8.5	4	40	25	30	13.8	0.08	0.1	0.0204	0.2582	901	12.5	1733	1.11	15.27
13	10	30	8.5	5	10	25	30	11	0.08	0.1	0.026	0.3231	225	2.7	1733	0.42	1.241
14	10	30	8.5	5	20	25	30	11.8	0.08	0.1	0.0244	0.3231	451	5.4	1733	0.68	4.021
15	10	30	8.5	5	30	25	30	12.4	0.08	0.1	0.0232	0.3231	676	8.0	1733	0.91	8.041
16	10	30	8.5	5	40	25	30	13.4	0.08	0.1	0.0212	0.3231	901	10.3	1733	1.11	12.59

Table (A - 2)Experimental data at (T =10 °C, d= 10 mm, H =30 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_2 mol/liter	C_3 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
17	10	30	8.5	2	10	25	30	13.4	0.084	0.1	0.0236	0.1084	272	8.0	1186	0.48	3.447
18	10	30	8.5	2	20	25	30	14.2	0.084	0.1	0.022	0.1084	544	15.8	1186	0.78	11.13
19	10	30	8.5	2	30	25	30	15	0.084	0.1	0.0204	0.1084	816	23.3	1186	1.03	21.76
20	10	30	8.5	2	40	25	30	15.6	0.084	0.1	0.0192	0.1084	1088	30.8	1186	1.27	35.32
21	10	30	8.5	3	10	25	30	12.8	0.084	0.1	0.0248	0.1628	272	5.4	1186	0.48	2.32
22	10	30	8.5	3	20	25	30	13.6	0.084	0.1	0.0232	0.1628	544	10.7	1186	0.78	7.545
23	10	30	8.5	3	30	25	30	14.5	0.084	0.1	0.0214	0.1628	816	15.7	1186	1.03	14.71
24	10	30	8.5	3	40	25	30	15.2	0.084	0.1	0.02	0.1628	1088	20.7	1186	1.27	23.75
25	10	30	8.5	4	10	25	30	12.3	0.084	0.1	0.0258	0.2173	272	4.1	1186	0.48	1.774
26	10	30	8.5	4	20	25	30	13	0.084	0.1	0.0244	0.2173	544	8.3	1186	0.78	5.845
27	10	30	8.5	4	30	25	30	13.7	0.084	0.1	0.023	0.2173	816	12.5	1186	1.03	11.68
28	10	30	8.5	4	40	25	30	14.7	0.084	0.1	0.021	0.2173	1088	16.1	1186	1.27	18.42
29	10	30	8.5	5	10	25	30	11.7	0.084	0.1	0.027	0.2719	272	3.4	1186	0.48	1.468
30	10	30	8.5	5	20	25	30	12.4	0.084	0.1	0.0256	0.2719	544	6.9	1186	0.78	4.853
31	10	30	8.5	5	30	25	30	13.3	0.084	0.1	0.0238	0.2719	816	10.2	1186	1.03	9.562
32	10	30	8.5	5	40	25	30	14.3	0.084	0.1	0.0218	0.2719	1088	13.2	1186	1.27	15.14

Table (A - 3)Experimental data at (T =15 °C, d= 10 mm, H =30 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_1 mol/liter	C_2 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
33	10	30	8.5	2	10	25	30	13.9	0.084	0.1	0.0226	0.0924	310	9.2	882	0.52	3.73
34	10	30	8.5	2	20	25	30	14.7	0.084	0.1	0.021	0.0924	620	18.3	882	0.85	12.08
35	10	30	8.5	2	30	25	30	15.5	0.084	0.1	0.0194	0.0924	931	27.0	882	1.13	23.67
36	10	30	8.5	2	40	25	30	16.2	0.084	0.1	0.018	0.0924	1241	35.4	882	1.39	38.07
37	10	30	8.5	3	10	25	30	13.3	0.084	0.1	0.0238	0.1387	310	6.2	882	0.52	2.504
38	10	30	8.5	3	20	25	30	14.2	0.084	0.1	0.022	0.1387	620	12.3	882	0.85	8.092
39	10	30	8.5	3	30	25	30	15.3	0.084	0.1	0.0198	0.1387	931	17.6	882	1.13	15.47
40	10	30	8.5	3	40	25	30	15.8	0.084	0.1	0.0188	0.1387	1241	23.8	882	1.39	25.59
41	10	30	8.5	4	10	25	30	12.8	0.084	0.1	0.0248	0.1851	310	4.7	882	0.52	1.913
42	10	30	8.5	4	20	25	30	13.8	0.084	0.1	0.0228	0.1851	620	9.3	882	0.85	6.159
43	10	30	8.5	4	30	25	30	14.5	0.084	0.1	0.0214	0.1851	931	14.1	882	1.13	12.34
44	10	30	8.5	4	40	25	30	15.2	0.084	0.1	0.02	0.1851	1241	18.7	882	1.39	20.09
45	10	30	8.5	5	10	25	30	12.5	0.084	0.1	0.0254	0.2316	310	3.8	882	0.52	1.545
46	10	30	8.5	5	20	25	30	13.1	0.084	0.1	0.0242	0.2316	620	7.8	882	0.85	5.171
47	10	30	8.5	5	30	25	30	14	0.084	0.1	0.0224	0.2316	931	11.6	882	1.13	10.22
48	10	30	8.5	5	40	25	30	15.1	0.084	0.1	0.0202	0.2316	1241	14.9	882	1.39	16.04

Table (A - 4)Experimental data at (T =20 °C, d= 10 mm, H =30 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (Bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_1 mol/liter	C_2 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
49	10	30	8.5	2	10	25	30	14	0.082	0.1	0.0212	0.0794	354	10.3	667	0.57	3.951
50	10	30	8.5	2	20	25	30	14.6	0.082	0.1	0.02	0.0794	707	21.1	667	0.93	13.12
51	10	30	8.5	2	30	25	30	15.3	0.082	0.1	0.0186	0.0794	1061	31.4	667	1.24	26.09
52	10	30	8.5	2	40	25	30	16.1	0.082	0.1	0.017	0.0794	1415	40.9	667	1.53	41.58
53	10	30	8.5	3	10	25	30	13.4	0.082	0.1	0.0224	0.1192	354	6.9	667	0.57	2.648
54	10	30	8.5	3	20	25	30	14.3	0.082	0.1	0.0206	0.1192	707	13.8	667	0.93	8.577
55	10	30	8.5	3	30	25	30	15.1	0.082	0.1	0.019	0.1192	1061	20.5	667	1.24	16.97
56	10	30	8.5	3	40	25	30	15.7	0.082	0.1	0.0178	0.1192	1415	27.5	667	1.53	27.91
57	10	30	8.5	4	10	25	30	12.8	0.082	0.1	0.0236	0.159	354	5.4	667	0.57	2.044
58	10	30	8.5	4	20	25	30	13.8	0.082	0.1	0.0216	0.159	707	10.6	667	0.93	6.6
59	10	30	8.5	4	30	25	30	14.7	0.082	0.1	0.0198	0.159	1061	15.7	667	1.24	13
60	10	30	8.5	4	40	25	30	15.4	0.082	0.1	0.0184	0.159	1415	20.9	667	1.53	21.23
61	10	30	8.5	5	10	25	30	12.4	0.082	0.1	0.0244	0.1989	354	4.4	667	0.57	1.665
62	10	30	8.5	5	20	25	30	13.2	0.082	0.1	0.0228	0.1989	707	8.8	667	0.93	5.504
63	10	30	8.5	5	30	25	30	14.2	0.082	0.1	0.0208	0.1989	1061	13.0	667	1.24	10.3
64	10	30	8.5	5	40	25	30	15	0.082	0.1	0.0192	0.1989	1415	17.2	667	1.53	17.52

Table (A -5)Experimental data at (T = 5 °C, d= 10 mm, H = 60 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_1 mol/liter	C_2 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
65	10	60	16.7	2	10	25	30	15	0.084	0.1	0.0204	0.1288	225	5.4	1733	0.33	2.00764
66	10	60	16.7	2	20	25	30	15.9	0.084	0.1	0.0186	0.1288	451	10.3	1733	0.54	6.20661
67	10	60	16.7	2	30	25	30	16.5	0.084	0.1	0.0174	0.1288	676	15.0	1733	0.73	12.0242
68	10	60	16.7	2	40	25	30	17.6	0.084	0.1	0.0152	0.1288	901	18.0	1733	0.89	17.6738
69	10	60	16.7	3	10	25	30	14.6	0.084	0.1	0.0212	0.1934	225	3.7	1733	0.33	1.3518
70	10	60	16.7	3	20	25	30	15.4	0.084	0.1	0.0196	0.1934	451	7.1	1733	0.54	4.25233
71	10	60	16.7	3	30	25	30	16.1	0.084	0.1	0.0182	0.1934	676	10.2	1733	0.73	8.18822
72	10	60	16.7	3	40	25	30	17.1	0.084	0.1	0.0162	0.1934	901	12.5	1733	0.89	12.3122
73	10	60	16.7	4	10	25	30	14.1	0.084	0.1	0.0222	0.2582	225	2.8	1733	0.33	1.04674
74	10	60	16.7	4	20	25	30	14.9	0.084	0.1	0.0206	0.2582	451	5.5	1733	0.54	3.30881
75	10	60	16.7	4	30	25	30	15.6	0.084	0.1	0.0192	0.2582	676	8.0	1733	0.73	6.40186
76	10	60	16.7	4	40	25	30	16.5	0.084	0.1	0.0174	0.2582	901	10.0	1733	0.89	9.81915
77	10	60	16.7	5	10	25	30	13.7	0.084	0.1	0.023	0.3231	225	2.3	1733	0.33	0.85979
78	10	60	16.7	5	20	25	30	14.6	0.084	0.1	0.0212	0.3231	451	4.5	1733	0.54	2.70074
79	10	60	16.7	5	30	25	30	15.3	0.084	0.1	0.0198	0.3231	676	6.5	1733	0.73	5.23936
80	10	60	16.7	5	40	25	30	16.1	0.084	0.1	0.0182	0.3231	901	8.3	1733	0.89	8.15986

Table (A - 6)Experimental data at (T =10 °C, d= 10 mm, H = 60 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_1 mol/liter	C_2 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
81	10	60	16.7	2	10	25	30	15.4	0.083	0.1	0.019	0.1084	272	6.2	1186	0.38	2.12363
82	10	60	16.7	2	20	25	30	16.3	0.083	0.1	0.0172	0.1084	544	11.6	1186	0.62	6.55549
83	10	60	16.7	2	30	25	30	17.1	0.083	0.1	0.0156	0.1084	816	16.5	1186	0.83	12.3591
84	10	60	16.7	2	40	25	30	17.8	0.083	0.1	0.0142	0.1084	1088	20.8	1186	1.02	19.1017
85	10	60	16.7	3	10	25	30	15.1	0.083	0.1	0.0196	0.1628	272	4.1	1186	0.38	1.41364
86	10	60	16.7	3	20	25	30	15.9	0.083	0.1	0.018	0.1628	544	7.9	1186	0.62	4.44572
87	10	60	16.7	3	30	25	30	16.4	0.083	0.1	0.017	0.1628	816	11.7	1186	0.83	8.77227
88	10	60	16.7	3	40	25	30	17.4	0.083	0.1	0.015	0.1628	1088	14.3	1186	1.02	13.1503
89	10	60	16.7	4	10	25	30	14.6	0.083	0.1	0.0206	0.2173	272	3.2	1186	0.38	1.09758
90	10	60	16.7	4	20	25	30	15.3	0.083	0.1	0.0192	0.2173	544	6.2	1186	0.62	3.50997
91	10	60	16.7	4	30	25	30	15.9	0.083	0.1	0.018	0.2173	816	9.2	1186	0.83	6.87769
92	10	60	16.7	4	40	25	30	16.6	0.083	0.1	0.0166	0.2173	1088	11.8	1186	1.02	10.8111
93	10	60	16.7	5	10	25	30	13.9	0.083	0.1	0.022	0.2719	272	2.7	1186	0.38	0.92979
94	10	60	16.7	5	20	25	30	14.8	0.083	0.1	0.0202	0.2719	544	5.2	1186	0.62	2.92905
95	10	60	16.7	5	30	25	30	15.5	0.083	0.1	0.0188	0.2719	816	7.6	1186	0.83	5.69906
96	10	60	16.7	5	40	25	30	16.4	0.083	0.1	0.017	0.2719	1088	9.6	1186	1.02	8.78342

Table (A - 7)Experimental data at (T =15 °C, d= 10 mm, H = 60 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_1 mol/liter	C_2 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
97	10	60	16.7	2	10	25	30	15.8	0.08	0.1	0.0164	0.0924	310	6.3	882	0.42	2.03539
98	10	60	16.7	2	20	25	30	16.5	0.08	0.1	0.015	0.0924	620	12.1	882	0.68	6.39068
99	10	60	16.7	2	30	25	30	17.3	0.08	0.1	0.0134	0.0924	931	16.9	882	0.91	11.9159
100	10	60	16.7	2	40	25	30	18	0.08	0.1	0.012	0.0924	1241	21.1	882	1.11	18.197
101	10	60	16.7	3	10	25	30	15.5	0.08	0.1	0.017	0.1387	310	4.2	882	0.42	1.36205
102	10	60	16.7	3	20	25	30	16.2	0.08	0.1	0.0156	0.1387	620	8.1	882	0.68	4.30457
103	10	60	16.7	3	30	25	30	16.9	0.08	0.1	0.0142	0.1387	931	11.7	882	0.91	8.2143
104	10	60	16.7	3	40	25	30	17.7	0.08	0.1	0.0126	0.1387	1241	14.5	882	1.11	12.4579
105	10	60	16.7	4	10	25	30	15.2	0.08	0.1	0.0176	0.1851	310	3.2	882	0.42	1.04078
106	10	60	16.7	4	20	25	30	15.7	0.08	0.1	0.0166	0.1851	620	6.4	882	0.68	3.38981
107	10	60	16.7	4	30	25	30	16.6	0.08	0.1	0.0148	0.1851	931	9.0	882	0.91	6.33785
108	10	60	16.7	4	40	25	30	17.4	0.08	0.1	0.0132	0.1851	1241	11.2	882	1.11	9.67757
109	10	60	16.7	5	10	25	30	14.6	0.08	0.1	0.0188	0.2316	310	2.7	882	0.42	0.88188
110	10	60	16.7	5	20	25	30	15.4	0.08	0.1	0.0172	0.2316	620	5.3	882	0.68	2.784
111	10	60	16.7	5	30	25	30	16.2	0.08	0.1	0.0156	0.2316	931	7.5	882	0.91	5.30343
112	10	60	16.7	5	40	25	30	17	0.08	0.1	0.014	0.2316	1241	9.5	882	1.11	8.15627

Table (A - 8)Experimental data at (T =20 °C, d= 10 mm, H = 60 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (Bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_1 mol/liter	C_2 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
113	10	60	16.7	2	10	25	30	16.8	0.08	0.1	0.0144	0.0794	354	6.5	667	0.46	1.98874
114	10	60	16.7	2	20	25	30	17.3	0.08	0.1	0.0134	0.0794	707	12.8	667	0.75	6.40403
115	10	60	16.7	2	30	25	30	18	0.08	0.1	0.012	0.0794	1061	18.1	667	1.00	12.0432
116	10	60	16.7	2	40	25	30	18.7	0.08	0.1	0.0106	0.0794	1415	22.4	667	1.22	18.2313
117	10	60	16.7	3	10	25	30	16.1	0.08	0.1	0.0158	0.1192	354	4.6	667	0.46	1.41319
118	10	60	16.7	3	20	25	30	16.6	0.08	0.1	0.0148	0.1192	707	9.2	667	0.75	4.59308
119	10	60	16.7	3	30	25	30	17.4	0.08	0.1	0.0132	0.1192	1061	13.0	667	1.00	8.62622
120	10	60	16.7	3	40	25	30	18	0.08	0.1	0.012	0.1192	1415	16.6	667	1.22	13.4999
121	10	60	16.7	4	10	25	30	15.6	0.08	0.1	0.0168	0.159	354	3.6	667	0.46	1.10979
122	10	60	16.7	4	20	25	30	16.4	0.08	0.1	0.0152	0.159	707	7.0	667	0.75	3.48122
123	10	60	16.7	4	30	25	30	16.9	0.08	0.1	0.0142	0.159	1061	10.3	667	1.00	6.87597
124	10	60	16.7	4	40	25	30	17.6	0.08	0.1	0.0128	0.159	1415	13.1	667	1.22	10.6782
125	10	60	16.7	5	10	25	30	15.2	0.08	0.1	0.0176	0.1989	354	3.0	667	0.46	0.92076
126	10	60	16.7	5	20	25	30	15.8	0.08	0.1	0.0164	0.1989	707	6.0	667	0.75	2.98133
127	10	60	16.7	5	30	25	30	16.5	0.08	0.1	0.015	0.1989	1061	8.7	667	1.00	5.76313
128	10	60	16.7	5	40	25	30	17.2	0.08	0.1	0.0136	0.1989	1415	11.1	667	1.22	9.01115

Table (A - 9)Experimental data at (T =5 °C, d= 10 mm, H = 90 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_1 mol/liter	C_2 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
129	10	90	24.2	2	10	25	30	16.8	0.092	0.1	0.0216	0.1288	225	5.8	1733	0.30	1.89873
130	10	90	24.2	2	20	25	30	17.5	0.092	0.1	0.0202	0.1288	451	11.1	1733	0.48	5.92934
131	10	90	24.2	2	30	25	30	18.1	0.092	0.1	0.019	0.1288	676	16.2	1733	0.64	11.5236
132	10	90	24.2	2	40	25	30	19.3	0.092	0.1	0.0166	0.1288	901	19.3	1733	0.79	16.8224
133	10	90	24.2	3	10	25	30	16.2	0.092	0.1	0.0228	0.1934	225	3.9	1733	0.30	1.27673
134	10	90	24.2	3	20	25	30	17.2	0.092	0.1	0.0208	0.1934	451	7.4	1733	0.48	3.9529
135	10	90	24.2	3	30	25	30	17.8	0.092	0.1	0.0196	0.1934	676	10.9	1733	0.64	7.75356
136	10	90	24.2	3	40	25	30	18.7	0.092	0.1	0.0178	0.1934	901	13.5	1733	0.79	11.7884
137	10	90	24.2	4	10	25	30	15.9	0.092	0.1	0.0234	0.2582	225	3.0	1733	0.30	0.97491
138	10	90	24.2	4	20	25	30	16.9	0.092	0.1	0.0214	0.2582	451	5.6	1733	0.48	3.01774
139	10	90	24.2	4	30	25	30	17.3	0.092	0.1	0.0206	0.2582	676	8.4	1733	0.64	6.00637
140	10	90	24.2	4	40	25	30	18.1	0.092	0.1	0.019	0.2582	901	10.7	1733	0.79	9.33219
141	10	90	24.2	5	10	25	30	15.5	0.092	0.1	0.0242	0.3231	225	2.4	1733	0.30	0.79894
142	10	90	24.2	5	20	25	30	16.4	0.092	0.1	0.0224	0.3231	451	4.7	1733	0.48	2.50606
143	10	90	24.2	5	30	25	30	17	0.092	0.1	0.0212	0.3231	676	6.9	1733	0.64	4.90257
144	10	90	24.2	5	40	25	30	17.7	0.092	0.1	0.0198	0.3231	901	8.9	1733	0.79	7.72116

Table (A - 10)Experimental data at (T =10 °C, d= 10 mm, H = 90 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_1 mol/liter	C_2 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
145	10	90	24.2	2	10	25	30	17.2	0.092	0.1	0.0208	0.1084	272	6.7	1186	0.34	2.067
146	10	90	24.2	2	20	25	30	18.1	0.092	0.1	0.019	0.1084	544	12.8	1186	0.55	6.395
147	10	90	24.2	2	30	25	30	18.8	0.092	0.1	0.0176	0.1084	816	18.4	1186	0.74	12.25
148	10	90	24.2	2	40	25	30	19.5	0.092	0.1	0.0162	0.1084	1088	23.3	1186	0.90	19.02
149	10	90	24.2	3	10	25	30	16.8	0.092	0.1	0.0216	0.1628	272	4.5	1186	0.34	1.381
150	10	90	24.2	3	20	25	30	17.8	0.092	0.1	0.0196	0.1628	544	8.5	1186	0.55	4.257
151	10	90	24.2	3	30	25	30	18.6	0.092	0.1	0.018	0.1628	816	12.2	1186	0.74	8.1
152	10	90	24.2	3	40	25	30	19.1	0.092	0.1	0.017	0.1628	1088	15.9	1186	0.90	12.96
153	10	90	24.2	4	10	25	30	16.3	0.092	0.1	0.0226	0.2173	272	3.5	1186	0.34	1.065
154	10	90	24.2	4	20	25	30	17.1	0.092	0.1	0.021	0.2173	544	6.7	1186	0.55	3.373
155	10	90	24.2	4	30	25	30	17.8	0.092	0.1	0.0196	0.2173	816	9.8	1186	0.74	6.535
156	10	90	24.2	4	40	25	30	18.4	0.092	0.1	0.0184	0.2173	1088	12.7	1186	0.90	10.4
157	10	90	24.2	5	10	25	30	15.6	0.092	0.1	0.024	0.2719	272	2.9	1186	0.34	0.896
158	10	90	24.2	5	20	25	30	16.6	0.092	0.1	0.022	0.2719	544	5.6	1186	0.55	2.8
159	10	90	24.2	5	30	25	30	17.4	0.092	0.1	0.0204	0.2719	816	8.1	1186	0.74	5.392
160	10	90	24.2	5	40	25	30	18.1	0.092	0.1	0.019	0.2719	1088	10.4	1186	0.90	8.513

Table (A - 11)Experimental data at (T =15 °C, d= 10 mm, H = 30 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_2 mol/liter	C_3 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
161	10	90	24.2	2	10	25	30	17.8	0.085	0.1	0.0154	0.0924	310	5.8	882	0.37	1.67
162	10	90	24.2	2	20	25	30	18.5	0.085	0.1	0.014	0.0924	620	11.0	882	0.61	5.174
163	10	90	24.2	2	30	25	30	19	0.085	0.1	0.013	0.0924	931	16.0	882	0.81	9.997
164	10	90	24.2	2	40	25	30	19.7	0.085	0.1	0.0116	0.0924	1241	19.7	882	0.99	15.107
165	10	90	24.2	3	10	25	30	17.2	0.085	0.1	0.0166	0.1387	310	4.1	882	0.37	1.167
166	10	90	24.2	3	20	25	30	17.6	0.085	0.1	0.0158	0.1387	620	8.1	882	0.61	3.8092
167	10	90	24.2	3	30	25	30	18.6	0.085	0.1	0.0138	0.1387	931	11.1	882	0.81	6.909
168	10	90	24.2	3	40	25	30	19.5	0.085	0.1	0.012	0.1387	1241	13.3	882	0.99	10.19
169	10	90	24.2	4	10	25	30	16.6	0.085	0.1	0.0178	0.1851	310	3.2	882	0.37	0.926
170	10	90	24.2	4	20	25	30	17.3	0.085	0.1	0.0164	0.1851	620	6.2	882	0.61	2.922
171	10	90	24.2	4	30	25	30	18.3	0.085	0.1	0.0144	0.1851	931	8.5	882	0.81	5.339
172	10	90	24.2	4	40	25	30	19	0.085	0.1	0.013	0.1851	1241	10.7	882	0.99	8.2
173	10	90	24.2	5	10	25	30	16.2	0.085	0.1	0.0186	0.2316	310	2.7	882	0.37	0.767
174	10	90	24.2	5	20	25	30	16.9	0.085	0.1	0.0172	0.2316	620	5.2	882	0.61	2.43
175	10	90	24.2	5	30	25	30	17.6	0.085	0.1	0.0158	0.2316	931	7.5	882	0.81	4.658
176	10	90	24.2	5	40	25	30	18.2	0.085	0.1	0.0146	0.2316	1241	9.6	882	0.99	7.332

Table (A - 12)Experimental data at (T =20 °C, d=10 mm, H = 30 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_2 mol/liter	C_3 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
177	10	90	24.2	2	10	25	30	17.9	0.083	0.1	0.014	0.0794	354	6.2	667	0.41	1.693
178	10	90	24.2	2	20	25	30	18.5	0.083	0.1	0.0128	0.0794	707	12.0	667	0.67	5.306
179	10	90	24.2	2	30	25	30	19.1	0.083	0.1	0.0116	0.0794	1061	17.0	667	0.89	10.034
180	10	90	24.2	2	40	25	30	19.7	0.083	0.1	0.0104	0.0794	1415	21.2	667	1.09	15.316
181	10	90	24.2	3	10	25	30	17.1	0.083	0.1	0.0156	0.1192	354	4.5	667	0.41	1.224
182	10	90	24.2	3	20	25	30	17.6	0.083	0.1	0.0146	0.1192	707	8.9	667	0.67	3.944
183	10	90	24.2	3	30	25	30	18.5	0.083	0.1	0.0128	0.1192	1061	12.2	667	0.89	7.217
184	10	90	24.2	3	40	25	30	19.3	0.083	0.1	0.0112	0.1192	1415	14.9	667	1.09	10.765
185	10	90	24.2	4	10	25	30	16.7	0.083	0.1	0.0164	0.159	354	3.5	667	0.41	0.95
186	10	90	24.2	4	20	25	30	17.3	0.083	0.1	0.0152	0.159	707	6.8	667	0.67	3.033
187	10	90	24.2	4	30	25	30	18.1	0.083	0.1	0.0136	0.159	1061	9.6	667	0.89	5.68
188	10	90	24.2	4	40	25	30	18.9	0.083	0.1	0.012	0.159	1415	11.8	667	1.09	8.561
189	10	90	24.2	5	10	25	30	16.3	0.083	0.1	0.0172	0.1989	354	2.9	667	0.41	0.789
190	10	90	24.2	5	20	25	30	17	0.083	0.1	0.0158	0.1989	707	5.6	667	0.67	2.498
191	10	90	24.2	5	30	25	30	17.7	0.083	0.1	0.0144	0.1989	1061	8.1	667	0.89	4.774
192	10	90	24.2	5	40	25	30	18.4	0.083	0.1	0.013	0.1989	1415	10.2	667	1.09	7.374

Table (A - 13)Experimental data at (T =5 °C, d= 20 mm, H = 30 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_2 mol/liter	C_3 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
193	20	30	8.5	2	20	25	30	14.4	0.092	0.1	0.0264	0.1288	225	7.1	1733	0.42	3.2451
194	20	30	8.5	2	40	25	30	15.3	0.092	0.1	0.0246	0.1288	451	13.4	1733	0.68	10.062
195	20	30	8.5	2	60	25	30	15.9	0.092	0.1	0.0234	0.1288	676	19.5	1733	0.91	19.484
196	20	30	8.5	2	80	25	30	16.7	0.092	0.1	0.0218	0.1288	901	24.6	1733	1.11	30.116
197	20	30	8.5	3	20	25	30	14	0.092	0.1	0.0272	0.1934	225	4.7	1733	0.42	2.1443
198	20	30	8.5	3	40	25	30	14.8	0.092	0.1	0.0256	0.1934	451	9.0	1733	0.68	6.7406
199	20	30	8.5	3	60	25	30	15.5	0.092	0.1	0.0242	0.1934	676	13.0	1733	0.91	12.991
200	20	30	8.5	3	80	25	30	16.4	0.092	0.1	0.0224	0.1934	901	16.3	1733	1.11	19.992
201	20	30	8.5	4	20	25	30	13.5	0.092	0.1	0.0282	0.2582	225	3.6	1733	0.42	1.6362
202	20	30	8.5	4	40	25	30	14.2	0.092	0.1	0.0268	0.2582	451	6.9	1733	0.68	5.2025
203	20	30	8.5	4	60	25	30	15	0.092	0.1	0.0252	0.2582	676	10.0	1733	0.91	9.9798
204	20	30	8.5	4	80	25	30	15.9	0.092	0.1	0.0234	0.2582	901	12.6	1733	1.11	15.429
205	20	30	8.5	5	20	25	30	13.1	0.092	0.1	0.029	0.3231	225	2.9	1733	0.42	1.3305
206	20	30	8.5	5	40	25	30	13.9	0.092	0.1	0.0274	0.3231	451	5.6	1733	0.68	4.2069
207	20	30	8.5	5	60	25	30	14.5	0.092	0.1	0.0262	0.3231	676	8.2	1733	0.91	8.218
208	20	30	8.5	5	80	25	30	15.5	0.092	0.1	0.0242	0.3231	901	10.3	1733	1.11	12.644

Table (A - 14)Experimental data at (T =10 °C, d= 20 mm, H = 30 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_2 mol/liter	C_3 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
209	20	30	8.5	2	20	25	30	15.5	0.088	0.1	0.0218	0.1084	272	7.0	1186	0.48	2.9944
210	20	30	8.5	2	40	25	30	16.3	0.088	0.1	0.0202	0.1084	544	13.2	1186	0.78	9.2679
211	20	30	8.5	2	60	25	30	17.1	0.088	0.1	0.0186	0.1084	816	18.6	1186	1.03	17.384
212	20	30	8.5	2	80	25	30	17.7	0.088	0.1	0.0174	0.1084	1088	23.6	1186	1.27	27.104
213	20	30	8.5	3	20	25	30	14.9	0.088	0.1	0.023	0.1628	272	4.7	1186	0.48	2.0313
214	20	30	8.5	3	40	25	30	15.7	0.088	0.1	0.0214	0.1628	544	9.0	1186	0.78	6.3336
215	20	30	8.5	3	60	25	30	16.6	0.088	0.1	0.0196	0.1628	816	12.7	1186	1.03	11.847
216	20	30	8.5	3	80	25	30	17.3	0.088	0.1	0.0182	0.1628	1088	16.0	1186	1.27	18.364
217	20	30	8.5	4	20	25	30	14.4	0.088	0.1	0.024	0.2173	272	3.6	1186	0.48	1.5608
218	20	30	8.5	4	40	25	30	15.1	0.088	0.1	0.0226	0.2173	544	7.0	1186	0.78	4.9355
219	20	30	8.5	4	60	25	30	15.8	0.088	0.1	0.0212	0.2173	816	10.1	1186	1.03	9.48
220	20	30	8.5	4	80	25	30	16.8	0.088	0.1	0.0192	0.2173	1088	12.5	1186	1.27	14.33
221	20	30	8.5	5	20	25	30	13.8	0.088	0.1	0.0252	0.2719	272	3.0	1186	0.48	1.2971
222	20	30	8.5	5	40	25	30	14.5	0.088	0.1	0.0238	0.2719	544	5.9	1186	0.78	4.1168
223	20	30	8.5	5	60	25	30	15.4	0.088	0.1	0.022	0.2719	816	8.3	1186	1.03	7.7918
224	20	30	8.5	5	80	25	30	16.4	0.088	0.1	0.02	0.2719	1088	10.3	1186	1.27	11.835

Table (A - 15)Experimental data at (T =15 °C, d= 20 mm, H = 30 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_1 mol/liter	C_2 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	$Scx10^6$ (-)	δ (mm)
225	20	30	8.5	2	20	25	30	15.8	0.091	0.1	0.023	0.0924	310	9.0	882	0.52
226	20	30	8.5	2	40	25	30	16.6	0.091	0.1	0.0214	0.0924	620	17.2	882	0.85
227	20	30	8.5	2	60	25	30	17.4	0.091	0.1	0.0198	0.0924	931	24.4	882	1.13
228	20	30	8.5	2	80	25	30	18.1	0.091	0.1	0.0184	0.0924	1241	30.8	882	1.39
229	20	30	8.5	3	20	25	30	15.2	0.091	0.1	0.0242	0.1387	310	6.0	882	0.52
230	20	30	8.5	3	40	25	30	16.1	0.091	0.1	0.0224	0.1387	620	11.5	882	0.85
231	20	30	8.5	3	60	25	30	17.2	0.091	0.1	0.0202	0.1387	931	15.9	882	1.13
232	20	30	8.5	3	80	25	30	17.7	0.091	0.1	0.0192	0.1387	1241	20.7	882	1.39
233	20	30	8.5	4	20	25	30	14.7	0.091	0.1	0.0252	0.1851	310	4.6	882	0.52
234	20	30	8.5	4	40	25	30	15.7	0.091	0.1	0.0232	0.1851	620	8.7	882	0.85
235	20	30	8.5	4	60	25	30	16.4	0.091	0.1	0.0218	0.1851	931	12.7	882	1.13
236	20	30	8.5	4	80	25	30	17.1	0.091	0.1	0.0204	0.1851	1241	16.2	882	1.39
237	20	30	8.5	5	20	25	30	14.4	0.091	0.1	0.0258	0.2316	310	3.7	882	0.52
238	20	30	8.5	5	40	25	30	15	0.091	0.1	0.0246	0.2316	620	7.3	882	0.85
239	20	30	8.5	5	60	25	30	15.9	0.091	0.1	0.0228	0.2316	931	10.5	882	1.13
240	20	30	8.5	5	80	25	30	17	0.091	0.1	0.0206	0.2316	1241	12.9	882	1.39

Table (A - 16)Experimental data at (T =20 °C, d= 20 mm, H = 30 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_1 mol/liter	C_2 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)
241	20	30	8.5	2	20	25	30	15.9	0.091	0.1	0.0228	0.0794	354	10.7	667	0.57
242	20	30	8.5	2	40	25	30	16.5	0.091	0.1	0.0216	0.0794	707	20.9	667	0.93
243	20	30	8.5	2	60	25	30	17.2	0.091	0.1	0.0202	0.0794	1061	30.0	667	1.24
244	20	30	8.5	2	80	25	30	18	0.091	0.1	0.0186	0.0794	1415	37.6	667	1.53
245	20	30	8.5	3	20	25	30	15.3	0.091	0.1	0.024	0.1192	354	7.1	667	0.57
246	20	30	8.5	3	40	25	30	16.2	0.091	0.1	0.0222	0.1192	707	13.6	667	0.93
247	20	30	8.5	3	60	25	30	17	0.091	0.1	0.0206	0.1192	1061	19.4	667	1.24
248	20	30	8.5	3	80	25	30	17.6	0.091	0.1	0.0194	0.1192	1415	25.0	667	1.53
249	20	30	8.5	4	20	25	30	14.7	0.091	0.1	0.0252	0.159	354	5.5	667	0.57
250	20	30	8.5	4	40	25	30	15.7	0.091	0.1	0.0232	0.159	707	10.4	667	0.93
251	20	30	8.5	4	60	25	30	16.6	0.091	0.1	0.0214	0.159	1061	14.8	667	1.24
252	20	30	8.5	4	80	25	30	17.3	0.091	0.1	0.02	0.159	1415	19.0	667	1.53
253	20	30	8.5	5	20	25	30	14.3	0.091	0.1	0.026	0.1989	354	4.4	667	0.57
254	20	30	8.5	5	40	25	30	15.1	0.091	0.1	0.0244	0.1989	707	8.6	667	0.93
255	20	30	8.5	5	60	25	30	16.1	0.091	0.1	0.0224	0.1989	1061	12.2	667	1.24
256	20	30	8.5	5	80	25	30	16.9	0.091	0.1	0.0208	0.1989	1415	15.6	667	1.53

Table (A - 17)Experimental data at (T =5 °C, d= 20 mm, H =60 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_1 mol/liter	C_2 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
257	20	60	16.7	2	20	25	30	15.2	0.082	0.1	0.0188	0.1288	225	4.8	1733	0.33	1.774
258	20	60	16.7	2	40	25	30	16.1	0.082	0.1	0.017	0.1288	451	8.8	1733	0.54	5.308
259	20	60	16.7	2	60	25	30	16.7	0.082	0.1	0.0158	0.1288	676	12.5	1733	0.73	9.995
260	20	60	16.7	2	80	25	30	17.8	0.082	0.1	0.0136	0.1288	901	14.4	1733	0.89	14.17
261	20	60	16.7	3	20	25	30	14.8	0.082	0.1	0.0196	0.1934	225	3.3	1733	0.33	1.201
262	20	60	16.7	3	40	25	30	15.6	0.082	0.1	0.018	0.1934	451	6.1	1733	0.54	3.664
263	20	60	16.7	3	60	25	30	16.3	0.082	0.1	0.0166	0.1934	676	8.6	1733	0.73	6.854
264	20	60	16.7	3	80	25	30	17.3	0.082	0.1	0.0146	0.1934	901	10.2	1733	0.89	9.969
265	20	60	16.7	4	20	25	30	14.3	0.082	0.1	0.0206	0.2582	225	2.5	1733	0.33	0.935
266	20	60	16.7	4	40	25	30	15.1	0.082	0.1	0.019	0.2582	451	4.8	1733	0.54	2.866
267	20	60	16.7	4	60	25	30	15.8	0.082	0.1	0.0176	0.2582	676	6.7	1733	0.73	5.392
268	20	60	16.7	4	80	25	30	16.7	0.082	0.1	0.0158	0.2582	901	8.2	1733	0.89	8.02
269	20	60	16.7	5	20	25	30	13.9	0.082	0.1	0.0214	0.3231	225	2.1	1733	0.33	0.77
270	20	60	16.7	5	40	25	30	14.8	0.082	0.1	0.0196	0.3231	451	3.9	1733	0.54	2.347
271	20	60	16.7	5	60	25	30	15.5	0.082	0.1	0.0182	0.3231	676	5.5	1733	0.73	4.428
272	20	60	16.7	5	80	25	30	16.3	0.082	0.1	0.0166	0.3231	901	6.8	1733	0.89	6.699

Table (A - 18)Experimental data at (T =10 °C, d= 20 mm, H =60 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_1 mol/liter	C_2 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
273	20	60	16.7	2	20	25	30	15.6	0.082	0.1	0.018	0.1084	272	5.6	1186	0.38	1.922
274	20	60	16.7	2	40	25	30	16.5	0.082	0.1	0.0162	0.1084	544	10.2	1186	0.62	5.734
275	20	60	16.7	2	60	25	30	17.3	0.082	0.1	0.0146	0.1084	816	14.0	1186	0.83	10.47
276	20	60	16.7	2	80	25	30	18	0.082	0.1	0.0132	0.1084	1088	17.0	1186	1.02	15.67
277	20	60	16.7	3	20	25	30	15.3	0.082	0.1	0.0186	0.1628	272	3.7	1186	0.38	1.284
278	20	60	16.7	3	40	25	30	16.1	0.082	0.1	0.017	0.1628	544	6.9	1186	0.62	3.907
279	20	60	16.7	3	60	25	30	16.6	0.082	0.1	0.016	0.1628	816	10.0	1186	0.83	7.485
280	20	60	16.7	3	80	25	30	17.6	0.082	0.1	0.014	0.1628	1088	11.8	1186	1.02	10.85
281	20	60	16.7	4	20	25	30	14.8	0.082	0.1	0.0196	0.2173	272	2.9	1186	0.38	1
282	20	60	16.7	4	40	25	30	15.5	0.082	0.1	0.0182	0.2173	544	5.5	1186	0.62	3.099
283	20	60	16.7	4	60	25	30	16.1	0.082	0.1	0.017	0.2173	816	7.9	1186	0.83	5.894
284	20	60	16.7	4	80	25	30	16.8	0.082	0.1	0.0156	0.2173	1088	9.8	1186	1.02	8.989
285	20	60	16.7	5	20	25	30	14.1	0.082	0.1	0.021	0.2719	272	2.5	1186	0.38	0.851
286	20	60	16.7	5	40	25	30	15	0.082	0.1	0.0192	0.2719	544	4.6	1186	0.62	2.594
287	20	60	16.7	5	60	25	30	15.7	0.082	0.1	0.0178	0.2719	816	6.5	1186	0.83	4.899
288	20	60	16.7	5	80	25	30	16.6	0.082	0.1	0.016	0.2719	1088	8.0	1186	1.02	7.318

Table (A - 19)Experimental data at (T =15 °C, d= 20 mm, H =60 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_1 mol/liter	C_2 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
289	20	60	16.7	2	20	25	30	18	0.0862	0.1	0.01572	0.0924	310	5.7	882	0.42	1.858
290	20	60	16.7	2	40	25	30	18.7	0.086	0.1	0.0142	0.0924	620	10.6	882	0.68	5.578
291	20	60	16.7	2	60	25	30	19.5	0.086	0.1	0.0126	0.0924	931	14.3	882	0.91	10.03
292	20	60	16.7	2	80	25	30	20.2	0.086	0.1	0.0112	0.0924	1241	17.2	882	1.11	14.78
293	20	60	16.7	3	20	25	30	17.7	0.086	0.1	0.0162	0.1387	310	3.8	882	0.42	1.237
294	20	60	16.7	3	40	25	30	18.4	0.086	0.1	0.0148	0.1387	620	7.1	882	0.68	3.772
295	20	60	16.7	3	60	25	30	19.1	0.086	0.1	0.0134	0.1387	931	9.9	882	0.91	6.954
296	20	60	16.7	3	80	25	30	19.9	0.086	0.1	0.0118	0.1387	1241	11.8	882	1.11	10.17
297	20	60	16.7	4	20	25	30	17.4	0.086	0.1	0.0168	0.1851	310	2.9	882	0.42	0.948
298	20	60	16.7	4	40	25	30	17.9	0.086	0.1	0.0158	0.1851	620	5.6	882	0.68	2.983
299	20	60	16.7	4	60	25	30	18.8	0.086	0.1	0.014	0.1851	931	7.7	882	0.91	5.383
300	20	60	16.7	4	80	25	30	19.6	0.086	0.1	0.0124	0.1851	1241	9.2	882	1.11	7.933
301	20	60	16.7	5	20	25	30	16.8	0.086	0.1	0.018	0.2316	310	2.5	882	0.42	0.806
302	20	60	16.7	5	40	25	30	17.6	0.086	0.1	0.0164	0.2316	620	4.6	882	0.68	2.455
303	20	60	16.7	5	60	25	30	18.4	0.086	0.1	0.0148	0.2316	931	6.4	882	0.91	4.52
304	20	60	16.7	5	80	25	30	19.2	0.086	0.1	0.0132	0.2316	1241	7.8	882	1.11	6.714

Table (A - 20)Experimental data at (T =20 °C, d= 20 mm, H =60 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_1 mol/liter	C_2 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
305	20	60	16.7	2	20	25	30	19	0.092	0.1	0.0172	0.0794	354	7.5	667	0.46	2.31
306	20	60	16.7	2	40	25	30	19.5	0.092	0.1	0.0162	0.0794	707	14.5	667	0.75	7.266
307	20	60	16.7	2	60	25	30	20.2	0.092	0.1	0.0148	0.0794	1061	20.3	667	1.00	13.48
308	20	60	16.7	2	80	25	30	20.9	0.092	0.1	0.0134	0.0794	1415	24.8	667	1.22	20.24
309	20	60	16.7	3	20	25	30	18.3	0.092	0.1	0.0186	0.1192	354	5.2	667	0.46	1.605
310	20	60	16.7	3	40	25	30	18.8	0.092	0.1	0.0176	0.1192	707	10.2	667	0.75	5.087
311	20	60	16.7	3	60	25	30	19.6	0.092	0.1	0.016	0.1192	1061	14.2	667	1.00	9.42
312	20	60	16.7	3	80	25	30	20.2	0.092	0.1	0.0148	0.1192	1415	17.8	667	1.22	14.52
313	20	60	16.7	4	20	25	30	17.8	0.092	0.1	0.0196	0.159	354	4.1	667	0.46	1.245
314	20	60	16.7	4	40	25	30	18.6	0.092	0.1	0.018	0.159	707	7.7	667	0.75	3.825
315	20	60	16.7	4	60	25	30	19.1	0.092	0.1	0.017	0.159	1061	11.1	667	1.00	7.39
316	20	60	16.7	4	80	25	30	19.8	0.092	0.1	0.0156	0.159	1415	13.9	667	1.22	11.31
317	20	60	16.7	5	20	25	30	17.4	0.092	0.1	0.0204	0.1989	354	3.3	667	0.46	1.024
318	20	60	16.7	5	40	25	30	18	0.092	0.1	0.0192	0.1989	707	6.5	667	0.75	3.232
319	20	60	16.7	5	60	25	30	18.7	0.092	0.1	0.0178	0.1989	1061	9.2	667	1.00	6.127
320	20	60	16.7	5	80	25	30	19.4	0.092	0.1	0.0164	0.1989	1415	11.6	667	1.22	9.424

Table (A - 21)Experimental data at (T =5 °C, d= 20 mm, H =90 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_1 mol/liter	C_2 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
321	20	90	24.2	2	20	25	30	15.7	0.086	0.1	0.0202	0.1288	225	5.2	1733	0.30	1.697
322	20	90	24.2	2	40	25	30	16.4	0.086	0.1	0.0188	0.1288	451	9.8	1733	0.48	5.223
323	20	90	24.2	2	60	25	30	17	0.086	0.1	0.0176	0.1288	676	13.9	1733	0.64	9.883
324	20	90	24.2	2	80	25	30	18.2	0.086	0.1	0.0152	0.1288	901	16.1	1733	0.79	14.02
325	20	90	24.2	3	20	25	30	15.1	0.086	0.1	0.0214	0.1934	225	3.6	1733	0.30	1.167
326	20	90	24.2	3	40	25	30	16.1	0.086	0.1	0.0194	0.1934	451	6.6	1733	0.48	3.499
327	20	90	24.2	3	60	25	30	16.7	0.086	0.1	0.0182	0.1934	676	9.3	1733	0.64	6.648
328	20	90	24.2	3	80	25	30	17.6	0.086	0.1	0.0164	0.1934	901	11.3	1733	0.79	9.891
329	20	90	24.2	4	20	25	30	14.8	0.086	0.1	0.022	0.2582	225	2.7	1733	0.30	0.886
330	20	90	24.2	4	40	25	30	15.8	0.086	0.1	0.02	0.2582	451	5.0	1733	0.48	2.669
331	20	90	24.2	4	60	25	30	16.2	0.086	0.1	0.0192	0.2582	676	7.3	1733	0.64	5.197
332	20	90	24.2	4	80	25	30	17	0.086	0.1	0.0176	0.2582	901	9.0	1733	0.79	7.881
333	20	90	24.2	5	20	25	30	14.4	0.086	0.1	0.0228	0.3231	225	2.2	1733	0.30	0.728
334	20	90	24.2	5	40	25	30	15.3	0.086	0.1	0.021	0.3231	451	4.2	1733	0.48	2.225
335	20	90	24.2	5	60	25	30	15.9	0.086	0.1	0.0198	0.3231	676	6.0	1733	0.64	4.254
336	20	90	24.2	5	80	25	30	16.6	0.086	0.1	0.0184	0.3231	901	7.5	1733	0.79	6.545

Table (A - 22)Experimental data at (T =10 °C, d= 20 mm, H =90 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_1 mol/liter	C_2 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
337	20	90	24.2	2	20	25	30	16.1	0.086	0.1	0.0194	0.1084	272	6.0	1186	0.34	1.846
338	20	90	24.2	2	40	25	30	17	0.086	0.1	0.0176	0.1084	544	11.1	1186	0.55	5.535
339	20	90	24.2	2	60	25	30	17.7	0.086	0.1	0.0162	0.1084	816	15.5	1186	0.74	10.3
340	20	90	24.2	2	80	25	30	18.4	0.086	0.1	0.0148	0.1084	1088	19.0	1186	0.90	15.54
341	20	90	24.2	3	20	25	30	15.7	0.086	0.1	0.0202	0.1628	272	4.0	1186	0.34	1.24
342	20	90	24.2	3	40	25	30	16.7	0.086	0.1	0.0182	0.1628	544	7.4	1186	0.55	3.704
343	20	90	24.2	3	60	25	30	17.5	0.086	0.1	0.0166	0.1628	816	10.3	1186	0.74	6.844
344	20	90	24.2	3	80	25	30	18	0.086	0.1	0.0156	0.1628	1088	13.1	1186	0.90	10.66
345	20	90	24.2	4	20	25	30	15.2	0.086	0.1	0.0212	0.2173	272	3.1	1186	0.34	0.961
346	20	90	24.2	4	40	25	30	16	0.086	0.1	0.0196	0.2173	544	5.9	1186	0.55	2.683
347	20	90	24.2	4	60	25	30	16.7	0.086	0.1	0.0182	0.2173	816	8.4	1186	0.74	5.567
348	20	90	24.2	4	80	25	30	17.3	0.086	0.1	0.017	0.2173	1088	10.6	1186	0.90	8.624
349	20	90	24.2	5	20	25	30	14.5	0.086	0.1	0.0226	0.2719	272	2.6	1186	0.34	0.812
350	20	90	24.2	5	40	25	30	15.5	0.086	0.1	0.0206	0.2719	544	4.9	1186	0.55	2.461
351	20	90	24.2	5	60	25	30	16.3	0.086	0.1	0.019	0.2719	816	6.9	1186	0.74	4.61
352	20	90	24.2	5	80	25	30	17	0.086	0.1	0.0176	0.2719	1088	8.7	1186	0.90	7.085

Table (A - 23)Experimental data at (T =15 °C, d= 20 mm, H =90 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_2 mol/liter	C_3 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
353	20	90	24.2	2	20	25	30	17.5	0.086	0.1	0.0166	0.0924	310	6.1	882	0.37	1.744
354	20	90	24.2	2	40	25	30	18.2	0.086	0.1	0.0152	0.0924	620	11.3	882	0.61	5.295
355	20	90	24.2	2	60	25	30	18.7	0.086	0.1	0.0142	0.0924	931	16.1	882	0.81	10.03
356	20	90	24.2	2	80	25	30	19.4	0.086	0.1	0.0128	0.0924	1241	19.5	882	0.99	14.95
357	20	90	24.2	3	20	25	30	16.9	0.086	0.1	0.0178	0.1387	310	4.2	882	0.37	1.21
358	20	90	24.2	3	40	25	30	17.3	0.086	0.1	0.017	0.1387	620	8.2	882	0.61	3.852
359	20	90	24.2	3	60	25	30	18.3	0.086	0.1	0.015	0.1387	931	11.0	882	0.81	6.883
360	20	90	24.2	3	80	25	30	19.2	0.086	0.1	0.0132	0.1387	1241	13.1	882	0.99	10.02
361	20	90	24.2	4	20	25	30	16.3	0.086	0.1	0.019	0.1851	310	3.3	882	0.37	0.954
362	20	90	24.2	4	40	25	30	17	0.086	0.1	0.0176	0.1851	620	6.3	882	0.61	2.944
363	20	90	24.2	4	60	25	30	18	0.086	0.1	0.0156	0.1851	931	8.5	882	0.81	5.295
364	20	90	24.2	4	80	25	30	18.7	0.086	0.1	0.0142	0.1851	1241	10.4	882	0.99	8.001
365	20	90	24.2	5	20	25	30	15.9	0.086	0.1	0.0198	0.2316	310	2.7	882	0.37	0.787
366	20	90	24.2	5	40	25	30	16.6	0.086	0.1	0.0184	0.2316	620	5.2	882	0.61	2.439
367	20	90	24.2	5	60	25	30	17.3	0.086	0.1	0.017	0.2316	931	7.3	882	0.81	4.585
368	20	90	24.2	5	80	25	30	17.9	0.086	0.1	0.0158	0.2316	1241	9.3	882	0.99	7.083

Table (A - 24)Experimental data at (T = 20 °C, d= 20 mm, H =90 mm)

Ex. No.	d (mm)	H (mm)	θ Deg.	P (bar)	Q (lit/hr)	V_1 (ml)	V_2 (ml)	V_3 (ml)	C_2 mol/liter	C_3 mol/liter	C_A mol/liter	C_A* mol/liter	Re (-)	$K_L x10^6$ m/s	Sc (-)	δ (mm)	Sh (-)
369	20	90	24.2	2	20	25	30	17.6	0.086	0.1	0.0164	0.0794	354	7.1	667	0.41	1.934
370	20	90	24.2	2	40	25	30	18.2	0.086	0.1	0.0152	0.0794	707	13.4	667	0.67	5.957
371	20	90	24.2	2	60	25	30	18.8	0.086	0.1	0.014	0.0794	1061	18.8	667	0.89	11.13
372	20	90	24.2	2	80	25	30	19.4	0.086	0.1	0.0128	0.0794	1415	23.3	667	1.09	16.84
373	20	90	24.2	3	20	25	30	16.8	0.086	0.1	0.018	0.1192	354	5.0	667	0.41	1.369
374	20	90	24.2	3	40	25	30	17.3	0.086	0.1	0.017	0.1192	707	9.7	667	0.67	4.314
375	20	90	24.2	3	60	25	30	18.2	0.086	0.1	0.0152	0.1192	1061	13.2	667	0.89	7.824
376	20	90	24.2	3	80	25	30	19	0.086	0.1	0.0136	0.1192	1415	16.0	667	1.09	11.61
377	20	90	24.2	4	20	25	30	16.4	0.086	0.1	0.0188	0.159	354	3.9	667	0.41	1.052
378	20	90	24.2	4	40	25	30	17	0.086	0.1	0.0176	0.159	707	7.4	667	0.67	3.289
379	20	90	24.2	4	60	25	30	17.8	0.086	0.1	0.016	0.159	1061	10.3	667	0.89	6.083
380	20	90	24.2	4	80	25	30	18.6	0.086	0.1	0.0144	0.159	1415	12.6	667	1.09	9.095
381	20	90	24.2	5	20	25	30	16	0.086	0.1	0.0196	0.1989	354	3.2	667	0.41	0.867
382	20	90	24.2	5	40	25	30	16.7	0.086	0.1	0.0182	0.1989	707	6.1	667	0.67	2.69
383	20	90	24.2	5	60	25	30	17.4	0.086	0.1	0.0168	0.1989	1061	8.6	667	0.89	5.061
384	20	90	24.2	5	80	25	30	18.1	0.086	0.1	0.0154	0.1989	1415	10.7	667	1.09	7.721

الخلاصة :

تهدف الدراسة الحالية للتعرف تجريبيا" على طبيعة انتقال المادة للغشاء الساقط في الأنابيب اللولبية . وقد اجريت التجارب بأستعمال نظام غاز ثنائي أوكسيد الكاربون مع الماء وحساب معامل انتقال المادة في غشاء الماء الساقط (K_L) ولمتغيرات متعددة ؛ قطر الأنبوب (d = 10 and 20 mm) ؛معدل تدفق الماء (Q_L = 10 – 80 Liter / hr) ؛ درجة الحرارة (T = 5,10,15 and 20 °C) ؛ ضغط ثنائي أوكسيد الكاربون (P = 2,3,4 and 5 bar) ؛الدرجة بين محاولتين (H = 30,60 and 90 mm) أو زاوية الأنحراف (θ = 8.5,16.7 and 24.2 deg.) عند ثبوت قطر الأنبوب اللولبي (D = 100 mm) وثبوت طول الأنبوب (L = 3 m).

وتشير النتائج التجريبية الى ان معامل انتقال المادة يزداد مع زيادة عدد رينولدز للغشاء الساقط.ويزداد معامل أنتقال المادة أيضا" بزيادة زاوية الأنحراف ويقل مع زيادة ضغط غاز ثنائي أوكسيد الكاربون مع ثبوت باقي المتغيرات. ووجد أن معامل أنتقال لايعتمد على تغير درجة الحرارة للنظام. وقد تم أستنتاج المعادلة التالية من التصحيحات العملية لأثبات معامل أنتقال المادة K_L يتمثل بواسطة عدد شيرود المجاميع اللابعدية للتجارب (٣٨٤ تجربة) :-

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

عندما تكون قيمة $R^2 = 0.87$ والمعلومات التجريبية تعطى مع ±30 % من القيم المحسوبة

المعادلات التالية تشتق عند أختلاف ضغط النظام لغاز CO_2 مع معدل ±10 %

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

وتم استنتاج النتائج التجريبية لتأثير ضغط غاز ثاني اوكسيد الكاربون الكلي الذي يتمثل بواسطة المعادلة التالية عندما تكون قيمة $R^2 = 0.9862$.

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

شكر وتقدير

أتوجه بالشكر لله على هنئ عطائه ومحمود بلائه وتوالي سبوغ نعمائه.

اتقدم بالشكر الجزيل الى استاذي الدكتور (زيد عدنان عبد الرحمن) لمعاونته ومساندته اياي طوال فترة البحث. كما اتقدم بالشكر الى الدكتور (باسم عبيد حسن) لأسداء النصيحة لي خلال فترة البحث .

كما أتقدم بشكري وأمتناني الى جميع أساتذة و منتسبي قسم الهندسة الكيمياوية في(جامعة تكريت) لأبدائهم المساعدة العظيمة لي أثناء فترة البحث .

كما أتقدم بعظيم شكري وتقديري وأخلاصي الى روح والدي الغالي (رحمه الله).

كما اتقدم بالشكر الى كل من ساندني خلال فترة البحث ولاسيما أهلي وزملائي.

آمال قحطان عبدالله

٢٠٠٨

دراسة انتقال المادة للغشاء الساقط في الأنابيب اللولبية بأستخدام نظام ماء- غازثاني أوكسيد الكاربون

رسالة

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في الهندسة الكيمياوية

من قبل

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بكالوريوس في الهندسة الكيمياوية ٢٠٠٥

صفر ١٤٣٠هـ

شباط ٢٠٠٩م