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Experimental Study of Simultaneous Heat and Mass Transfer in Falling Film and Bubble Mode (LiCl) Absorbers

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ABSTRACT

The study involves lithium-Chloride absorption process for the falling film and bubble columns absorbers, working at the same operating conditions. The results obtained were used to analyze the transfer process during the absorption of water vapor in the aqueous solution of LiCl.

The performance of both absorbers was investigated for various solution flow rates (0.1-0.5)kg/min , various gas flow rates (1-9) lit/min and inlet solution concentration (40-50) wt% . Results showed that bubble absorber is superior to the falling film mode for mass and heat transfer and that the efficiency of bubble columns is more than that of falling film absorbers. Increasing the solution flow rates rarely affected the mass transfer, but improved the heat transfer. To evaluate the performance of mass and heat transfer, experimental results obtained were plotted as Nusselt and Sherwood number versus operating conditions respectively for falling film and bubble modes. A power law correlations were obtained for the objective functions (i.e., mass and heat transfer coefficients) with correlation coefficient between (0.91 and 0.97) .

Keywords:-falling film, bubble column , mass and heat transfer coefficients.

دراسة معامل انتقال الحرارة والكتلة عند تصميم معدات الامتصاص
(العمود الشعاعي) (عمود الطيف المتساقطة)

الخلاصة

معاملات انتقال الكتلة والحرارة تعتبر احدى القيم الاساسية المطلوبة لتصميم معدات الامتصاص والتبادل الحراري اضافة الى استخدامها كمقاييس معيارية في تحديد كفاءة اداء تلك المعدات. وتتأثر قيم هذه المعاملات بالظروف التشغيلية والابعاد الهندسية للمعدة.

البحث يهتم بدراسة تأثير الظروف التشغيلية على كفاءة أداء أنواع مختلفة من أعمدة الامتصاص (ألعمود الفقاعي وعمود الطبقة المتساقطة) .

- تدفق الغاز (بخار الماء) من 1-9 لتر/دقيقة.
- تدفق السائل (محلول كلوريد الليثيوم) من 0.1-0.9 كغم/دقيقة.

- تركيز السائل (40-50) % وزناً .

أظهرت النتائج البحثية و إن كفاءة عمود الفقاعي تزداد عنها في عمود الطبقة المتســاقطة و كما تم استنتاج علاقات تجريبية للمجاميع اللابعدية (Sh and Nu) مع الظروف التشغيلية المذكورة اعلاه. تم قياس معامل الارتباط (R) للعلاقات مع النتائج العملية بحدود 0.91-0.97 .

For Falling Film Mode

$$N_u = 0.0137\,\mathrm{Re}_{sol}^{0.5}\,\mathrm{Re}_{gas}^{0.03}\left(\frac{\Delta C}{C_{sol,i}}\right)^{0.15}\left(\frac{\Delta T}{T_i}\right)^{0.3}$$

$$Sh = 658.5\ \mathrm{Re}_{sol}^{0.02}\ \mathrm{Re}_{gas}^{0.96}\left(\frac{\Delta C}{C_{sol,i}}\right)^{0.064}$$

For Bubble Mode:

$$N_u = 3.13\,\mathrm{Re}_{sol}^{0.26}\ \mathrm{Re}_{gas}^{0.3}\left(\frac{\Delta C}{C_{sol,i}}\right)^{0.086}\left(\frac{\Delta T}{T_i}\right)^{0.068}$$

$$Sh = 43.57\,.\,\mathrm{Re}_{sol}^{0.04}\ \mathrm{Re}_{gas}^{0.28}\left(\frac{\Delta C}{C_{sol,i}}\right)^{0.046}$$

INTRODUCTION

One of the most alarms in global environmental problems of today is the increase of global temperature .This problems caused by the increasing of some pollutants concentration from many industrial plants. To minimize and control this effect, an efficient improvement must be used in absorption systems [(1)].Film and bubble columns are considered absorption tools which involve simultaneous heat and mass transfer in the gas – liquid system. The heat of absorption gives rise to temperature gradient leading to the transfer of heat while the temperature affects the vapor pressure component equilibrium at the interface between the two phases, which in turn influences mass transfer[(2)]. The absorber is a major component in the absorption systems. Its performance greatly affects the overall system performance. Falling film absorbers provide high transfer coefficient and are stable during operation, but have wetability and liquid distributors problem. Bubble columns provide high heat transfer coefficients, good wetability and good mixing, but require good vapor distribution [(3)].

Kange [(4)] studied the effect of inlet temperatures of liquid and vapor in falling film absorber for (NH_3 +H_2O) system. He found that higher (Nu. and Sh.) numbers were found using lower inlet liquid temperature (noticing the viscosity of the solution) and higher inlet vapor temperature (about 25 degree above its boiling point). Sung, H.Kim et. al [(5)] , studied ($NH_3.H_2O$) system in both falling film absorber and bubble absorber . Results showed that bubble may offer better performance for heat transfer operations. The characteristics of heat and mass transfer of falling film absorbers was studied by Babadi [6] . He found that adding additives ($ZnCl_2$, $CaCl_2$, LiOH ,$Li_2M_2O_4$) will increase heat and transfer coefficients. Theoretical analysis and experimental investigation of the performance of ozone bubble columns was studied by Gamal-EL-din [7]. The aim of the present study the falling film and bubble modes are compared at the same operating conditions of LiCl solution-vapor system (atmospheric conditions), and results are plotted in dimensionless groups.

MATERIAL AND METHODS [8, 9]

Table (1) Physical properties of H2O and Air

	ρ Kg/m3	μ Kg/m.sec	M.Wt	σ N/m	Cp j/mol.K
H_2O	998	1.002	18	0.728	4.18
Air	1.205	15.11	28	-------	1.005

Table (2) Physical properties of LiCl

LiCl solution	
Density (ρ)	$\rho_{sol} = \rho_{H2O} * SG$, $SG= .98 + 6.9*10^{-3} C_{sol} – 4.1*10^{-4} T$ where SG is the specific gravity of the solution .
Viscosity (μ)	$\mu= 3.2*^{10-5} * T^{-0.89} Cs^{4.17}$
Thermal conductivity (k)	$k = 0.198 T^{0.08} Cs^{-0.03}$

EXPERIMENTAL SETUP

The primary components of the experimental apparatus were absorber, solution tank; return solution tank, solution sampling system pumping and cooling water system. Figure (1) shows the compact experimental falling film and bubble column system. The absorber (2) is constructed of two concentric tubes which define the space in which absorption takes place. The stainless steel inner tube (1) has a 3.8 cm OD, a total length of 1.6m, and an effective test section length of approximately 85cm. The solution film was established on the outer surface of the stainless steel tube, while inside the tube, cooling water flow, vertically upward. The outer tube was made of Pyrex glass pipe permitting flow observation. The solution of LiCl was introduced to the distributor at the top of the absorber. The solution flows downward by gravity through the collector attached to the bottom of the absorber and interacts with the upward flowing Vapor where absorption occurs.

The enthalpy of the absorbed vapor and the heat of mixing were removed by the cooling water provided from cooling water tank (5) via cooling water pump (8). Bubble mode was operated by filling the space between concentric tubes (2) with LiCl, and bubbling water vapor counter currently through it via air /water injector

(13) Temperature managements were performed by K-type thermocouples calibrated to an accuracy of ± 0.1°C. Thermocouples measured the solution inlet and outlet temperature, the cooling water inlet and outlet temperature, and other relevant temperature. Calibrated flow meters were used to measure the solution, the cooling water and the air flow rates. The inlet and outlet solution concentrations were determined by density measurements utilizing a pycnometer. The effects of solution flow rate and gas flow rate were tested on the performance of both falling film and bubble column absorbers respectively. Main flow rate of solution was varied from (0.1 to 0.5) kg/min. Flow rate of gas was varied from (1 to 9) lit/min

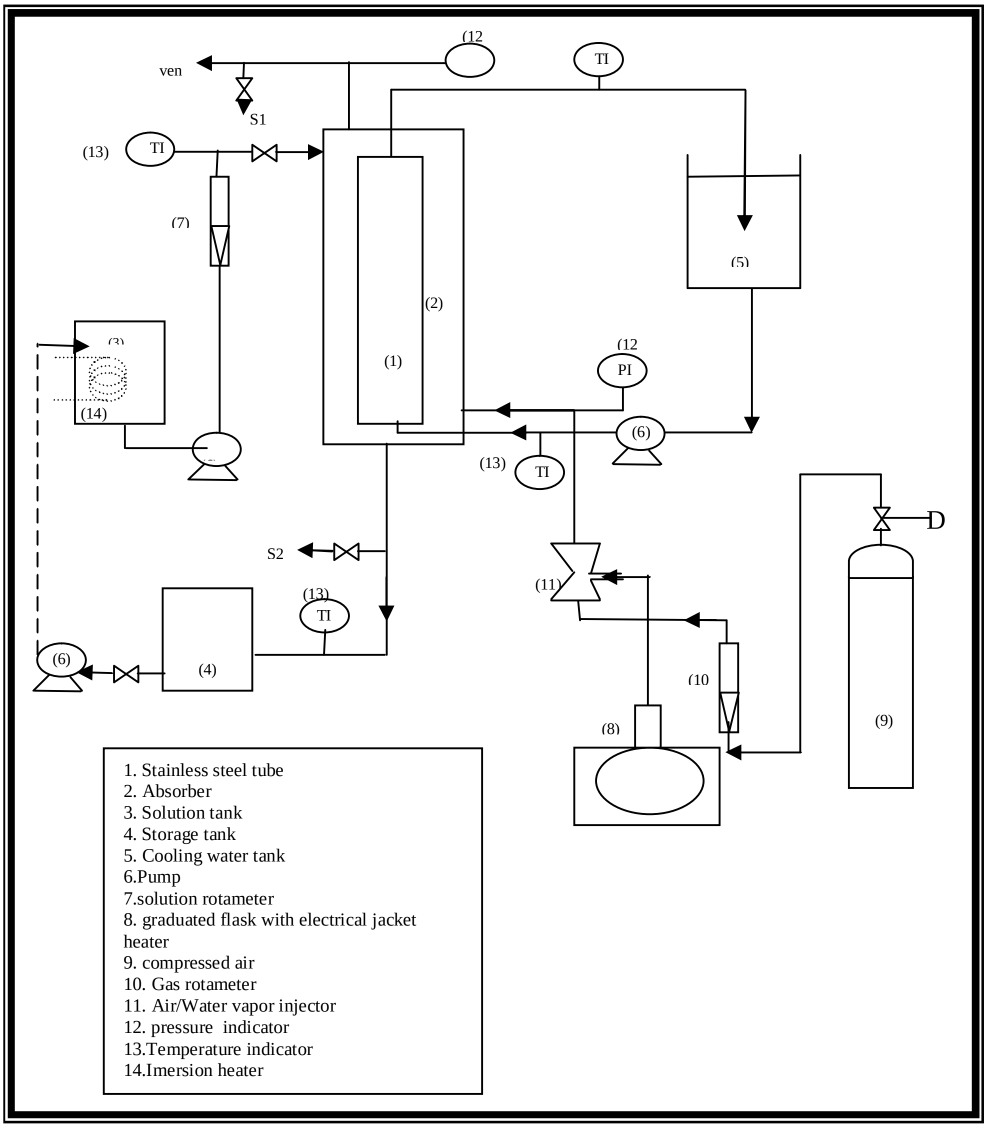

Figure (1) Experimental system

THEORY AND FUNDAMENTALS

1. Mass – Transfer rates :-

The absorption rate of the vapor (M_{abs}) can be determined from a simple mass balance:-

$$\dot{m}_{abs} = \dot{m}_{s.in} - \dot{m}_{s.out} \qquad \text{…. (1)}$$

The mass flow rate at the salt contained in the solution remains unchanged during the absorption process , therefore can be computed using either the inlet and outlet condition

$$\dot{m}_{abs} = \dot{m}_{s,in}\left[\frac{C_{sol,i}}{C_{sol,out}} - 1\right] \qquad \text{… (2)}$$

The absorption rate is expressed using the overall mass transfer **coefficient .**

$$\dot{m}_{abs} = K_m . A_{abs} . \Delta C \quad ^{(5)} \qquad \text{… (3)}$$

Where

A_{abs} =contact surface area between gas and liquid (m^2) for falling film absorber , A_{abs} is constant and equal to outside surface area of the coolant tube .

$$K_m = \frac{\dot{m}}{p . do . L . \Delta C} \qquad \text{….. (4)}$$

For bubble absorber, different empirical correlations were reported by many researchers of the field [5,7] :

$$K_L a = 2.62 \quad u_G^{0.85} \, uL0.19 \qquad \text{…… (5)}$$

$$\frac{K_{La} u_G}{g} = 149\left(\frac{u_G . u_L}{s}\right)^{1.76}\left(\frac{m_L{}^4 . g}{r_L . s^3}\right)^{-0.2}\left(\frac{m_G}{m_L}\right)^{0.24}\left(\frac{m_L}{r_L D_{AB}}\right)^{-0.6} \qquad \text{….. (6)}$$

Equation (6), seems to combine almost all variable used (u_G , u_L) , beside the effective physical properties of the fluids , the authors reported for equation (6) a correlation factor of 0.965, therefore it was used.

HEAT TRANSFER RATE

The heat transferred to the coolant can be expressed as the following heat transfer equation:-

$$\dot{q}_c = U . A \Delta T_{Lm} \quad ^{(10)} \qquad \text{…. (7)}$$

Where; -

$$\Delta T_{Lm} = \frac{\lfloor T_{sol,in} - T_{c,out} \rfloor - \lfloor\lfloor T_{sol,out} - T_{c,in} \rfloor\rfloor}{Ln\left[\frac{T_{sol,in} - T_{c,out}}{T_{sol,out} - T_{c,in}}\right]}$$

….. (8)

A: outside surface area of coolant tube m^2

U: overall heat transfer coefficient $kw/m^3.K$

Then (U) can be calculated as:- [10]

$$U = \frac{\dot{m}.c_p.(T_{c,out} - T_{c,in})}{p.d_o.L.\Delta T_{Lm}}$$ …… (9)

DIMENSIONLESS NUMBERS [5]

The dimensionless numbers are as the following table

Dimensionless number	Falling film	Bubble column
Reynolds No.	$Re=4m/do.\mu_l$	$Re=4r_H V\rho/\mu_l$
Sherwood No.	$Sh= K_l/D(\gamma_l^2/g)^{(1/3)}$	$Sh= 1.62(m/DL\rho)^{(1/3)}$
Nusselt No.	$Nu=h_{abs}/k_l(\gamma_l^2/g)^{(1/3)}$	$Nu= hL/k_l$

RESULTS AND DISCUSSION

Effect of solution flow rate

The effect of solution flow rate was evaluated for flow rates equivalent to liquid Reynolds number from (30 to 200) .Based upon the flow observation the flow structure near Ref = 30 and Ref = 60 were quite different .There was a significantly larger amplitude and higher frequency of film waviness near Ref = 60 ,compared to **Ref** =30 however , not much change was observed between Ref =60 and Ref =100 The observed phenomenon was the result of the combined effects of decreasing contact time between the solution and air /water vapor mixture and the mixing effect in the liquid film .Figure (2) shows that bubble column gives better performance than falling film once, this can be explain according to the theory of surface renewal (Danckwerts1970) as the mixing intensity increases the liquid film at the gas-Liquid interface will be renewed at a higher rate causing the local mass transfer coefficient (K_L) to increase. Increasing turbulence in the liquid phase will lead to higher turbulent shear stresses and the consequently causing the shearing of large bubbles into small bubbles. As a result, the gas bubble specific interfacial area (a) will increase leading to an increase in the overall mass transfer coefficient (K_La). More heat generated as the solution flow rate increased, this is shown clearly in Figure(3). Figures (4 and 9) show the effect of the solution flow rate on heat transfer coefficient. The heat transfer coefficient increased for certain range of liquid flow rate. Low solution flow rate effected transfer coefficient in a noticeable values, much more than at high flow rates. The difference of heat transfer coefficient between bubble and falling modes becomes smaller at higher gas flow rate. Figures (8 and 9) show the effect of solution flow rates on (Sh and Nu) numbers for both modes.

Effect of gas flow rate

Figures (5 and 7) show that bubble column has better value of heat and mass transfer coefficients than that the falling film mode for higher range of gas flow rates. Figure (7) indicate a remarkable notice for falling film, the heat transfer coefficient decreases with a slight rate as the gas flow rate increased gradually until a minimum value reached, then the heat transfer coefficient begins to increase with gas flow rate. The gradual increase in gas flow rate gives two simultaneous effects which worked in opposite direction on the heat transfer coefficient, first effect in the gradual decrease in gas .liquid contact time, which tends to decrease the heat transfer coefficient .The second effect is the gradual increase in the gas turbulence, which works to increase the heat transfer coefficient.

The first effect is predominant at low values of gas flow rate while the second become predominant at higher value of gas flow rate.

In bubble column the mixing intensity of gas bubbles increase gradually and proportionally with gas flow rate which resulting continuous increase in the heat transfer coefficient. Figures (10 and 11) show the effect of gas flow rates on (Sh and Nu) numbers.

Effect of liquid concentration

Figures (10 and 11) indicate that an increase in liquid concentration will have a negative effect on the coefficients of mass and heat. This is attributed to effect of liquid viscosity, which is proportion to the resistance of heat and mass transfer rates.

CORRELATION OF HEAT AND MASS TRANSFER COEFFICIENTS

From experimental results, the following correlations were proposed.Coefficients were estimated using regression analysis technique.

a)-For Falling Film Mode:-

$$N_u = 0.0137\,\mathrm{Re}_{sol}^{0.5}\ \mathrm{Re}_{gas}^{0.03}\left(\frac{\Delta C}{C_{sol,i}}\right)^{0.15}\left(\frac{\Delta T}{T_i}\right)^{0.3}$$

$$Sh = 658.5\ \ \mathrm{Re}_{sol}^{0.02}\ \ \mathrm{Re}_{gas}^{0.96}\left(\frac{\Delta C}{C_{sol,i}}\right)^{0.064}$$

b)-For Bubble Mode:

$$N_u = 3.13\,\mathrm{Re}_{sol}^{0.26}\ \mathrm{Re}_{gas}^{0.3}\left(\frac{\Delta C}{C_{sol,i}}\right)^{0.086}\left(\frac{\Delta T}{T_i}\right)^{0.068}$$

$$Sh = 43.57.\mathrm{Re}_{sol}^{0.04}\ \ \mathrm{Re}_{gas}^{0.28}\left(\frac{\Delta C}{C_{sol,i}}\right)^{0.046}$$

CONCLUSIONS

Falling film and bubble mode for ($LiCl–H_2O$) absorption were studied .The following conclusions were obtained :-

1-Mass and heat transfer coefficients of bubble column were more sensitive to increasing of gas flow rate than that of the falling film mode.

2-Rates of heat transferred in bubble column were less than that of the falling film column at lower values of gas flow rates.

3-From experimental results, bubble mode showed good performance at low solution flow rates and high gas flow rates.

4- Solution flow rates slightly affected the mass transfer coefficient, but clearly improved heat transfer coefficient for both bubble and falling film absorbers .

NOMENCLATURES:

A	Area	m^2
d_o	Outer diameter	m
D	Diffusivity	m^2/s
g	Gravitational acceleration	m/s^2
ΔC	Concentration difference	kg/m^3
C	Concentration	kg/m^3
h	Heat transfer coefficient	$W/m^2. K$
K_m	Overall mass transfer coefficient	m/min
k_{la}	Overall mass transfer coefficient	$m/min .m^2$
k	Thermal conductivity	W/m.K
L	length	m
Lm	Log mean temperature difference	
m′	Mass flow rate	kg/min
M.T.C	Mass transfer coefficient	m^3/min
Nu	Nusselt number $Nu_{bubble} = h.l/k$ $Nu_{falling} = (h_{abs}/k). (\gamma^2 /g)^{1/3}$	
T	*Temperature*	*K*
q	*Heat transfer rate*	*W*
r_H	*hydraulic* Radius	m
Re	Reynolds number $Re_{bubble} = 4r_H V\rho/\mu$ $Re_{falling} = 4m/do.\mu$	
Sh	*Sherwood number* $Sh_{bublle} = 1.6(m/D\ L\ \rho)^{1/3}$ $Sh_{falling} = (K/D).(\gamma^2/g)^{1/3}$	
u_G	Gas velocity	m/sec
u_L	liquid velocity	m/sec
U	Overall heat transfer coefficient.	$W/m^2.K$
V	Velocity	m/s

Greek symbols

γ	kinematic viscosity	m^2/s
μ_G	Gas dynamic viscosity	kg /m.s
μ_L	liquid dynamic viscosity	kg /m.s
ρ_l	liquid density	kg/m^3
ρ_G	Gas density	kg/m^3
σ	surface tension	N/m

Subscripts

abs	Absorption
c	coolent
l.G	liquid,gas
s..in	Solution in
s. out	Solution out

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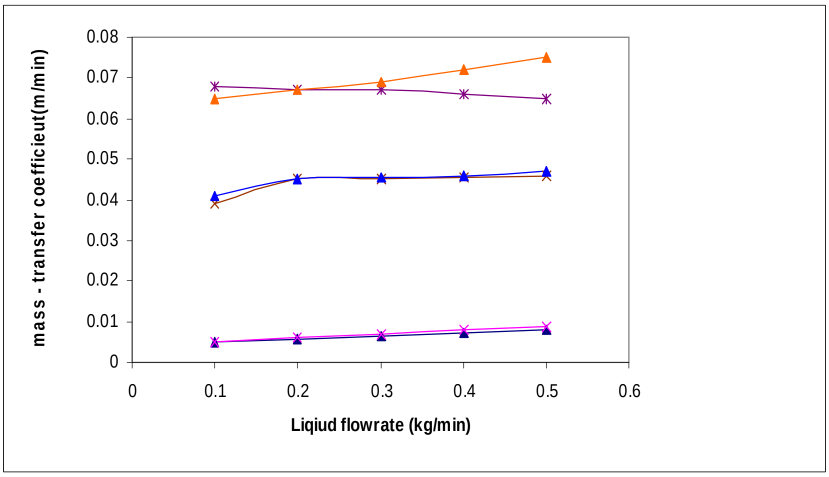


Figure (2) Effect of liquid flow rate on mass transfer coefficient with different gas flow rates

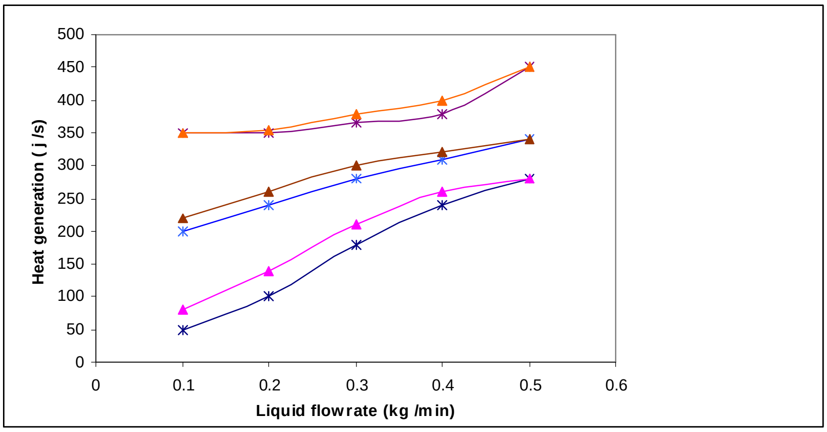


Figure (3) Heat generation as function of liquid flow rates with different gas flow rates .

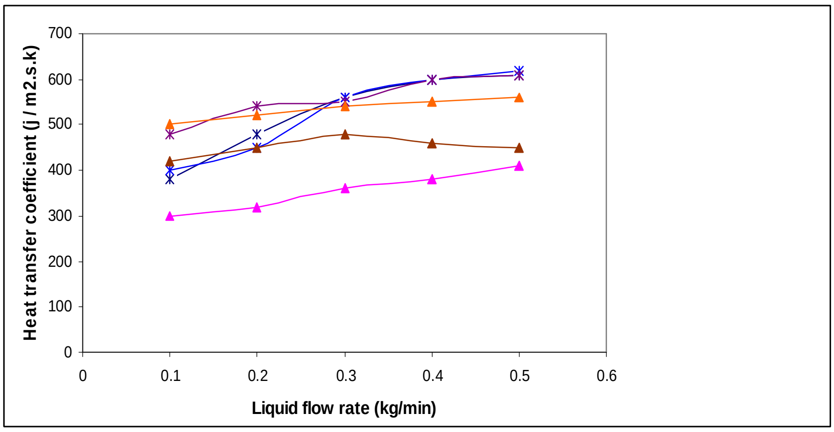


Figure (4) Effect of liquid flow rate on heat transfer Coefficient for different gas flow rates.

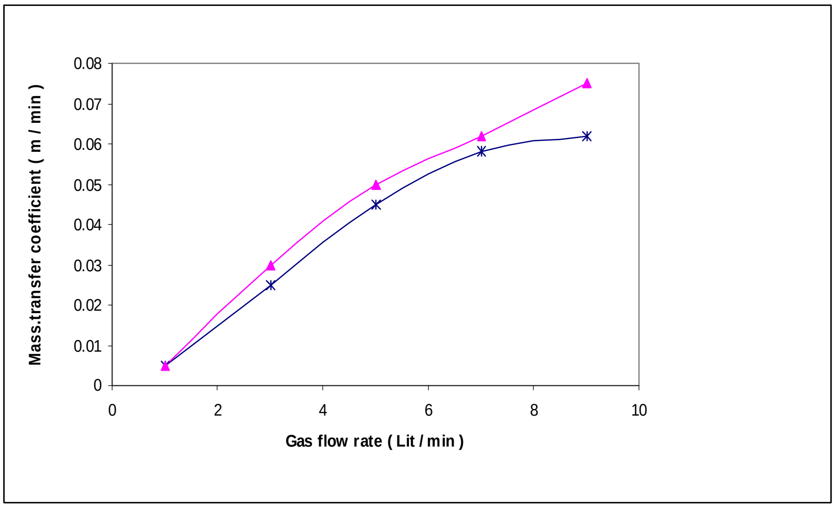


Figure (5) Effect of gas flow rates on mass transfer Coefficients.

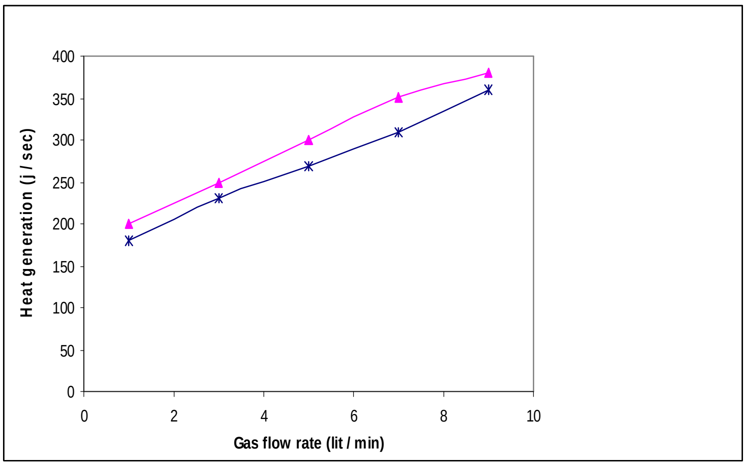
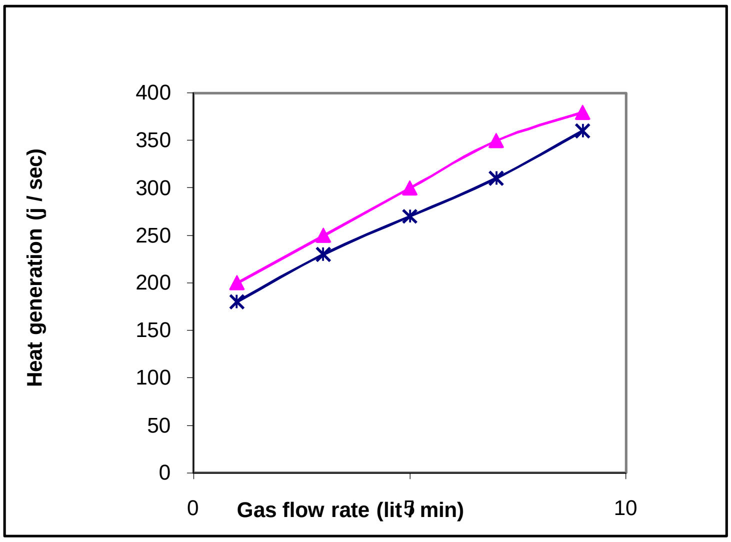


Figure (6) Heat generation as function of gas flow rate, for liquid flow rate of 0.3 kg/ min and 40% concentration

(a)



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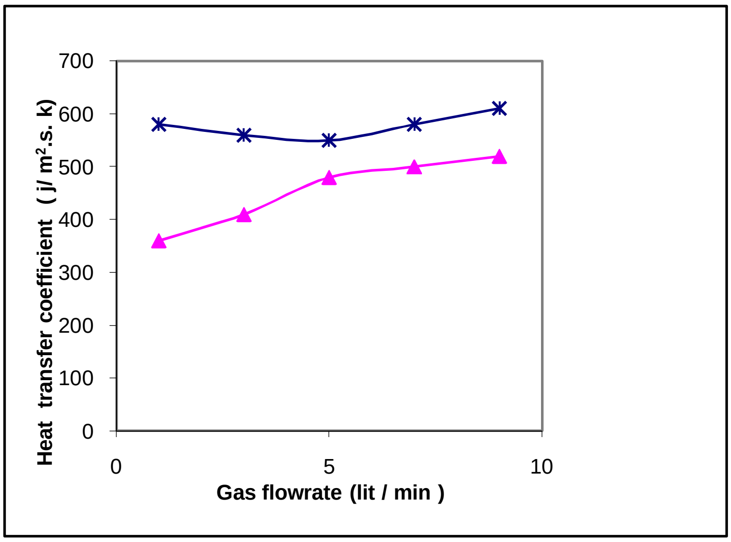
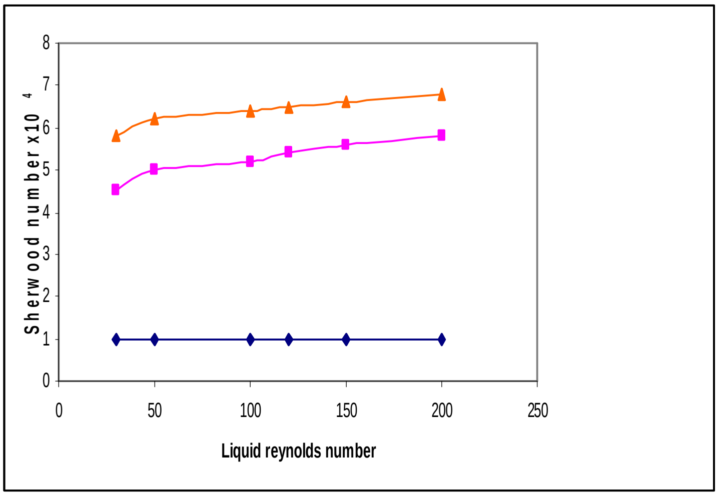


Figure (7) Effect of gas flow rate on heat transfer coefficient for different liquid flow rates concentration

a- 45% input solution with 0.3 kg/min flow rate

b- b- 40% input solution with 0.3 kg/min flow rate

(a)



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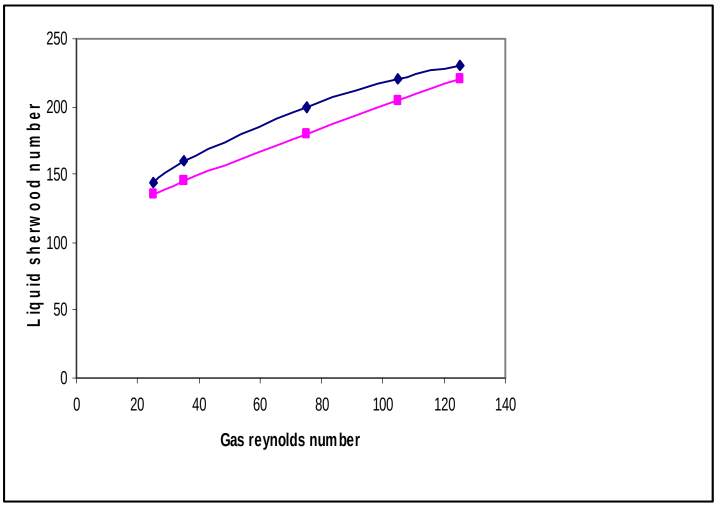
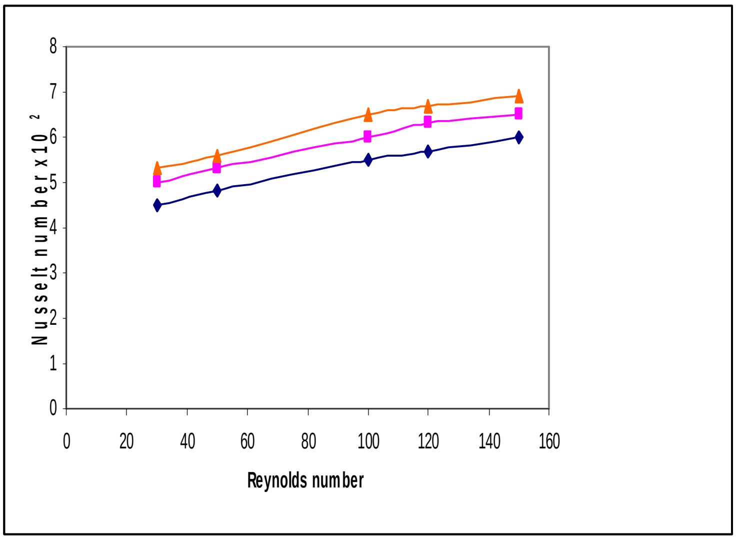
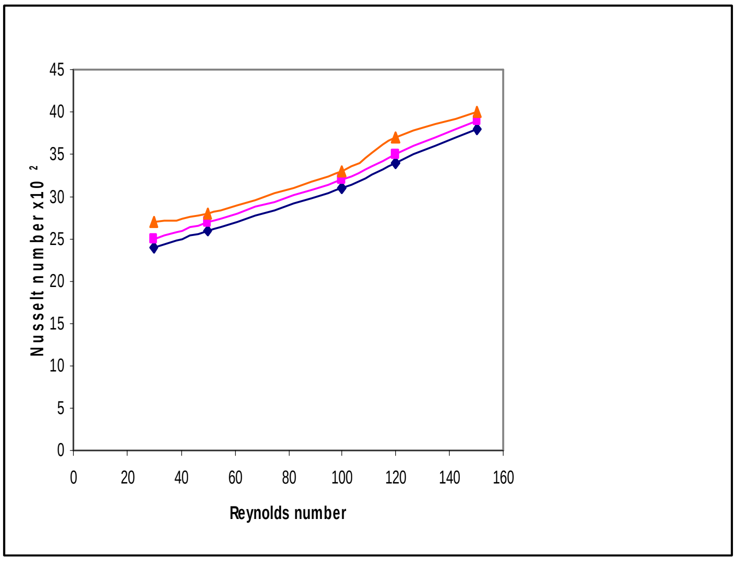


Figure (8) Liquid Reynolds number as function of Liquid Sherwood number with different gas flow rates
a- For falling film b- bubble column

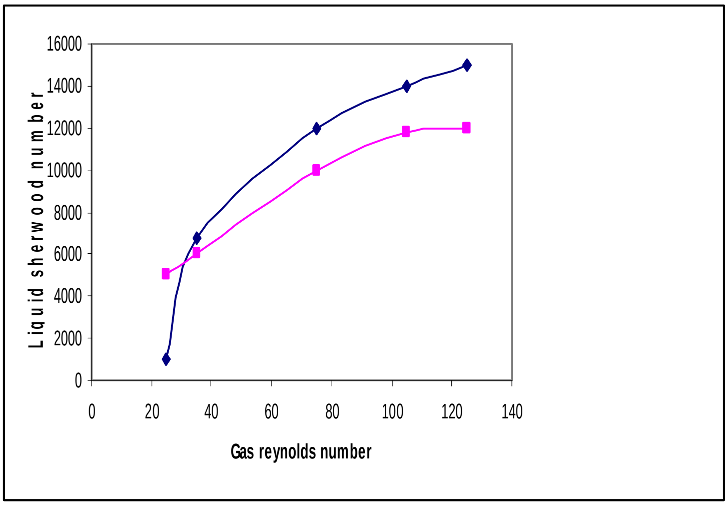


(a)

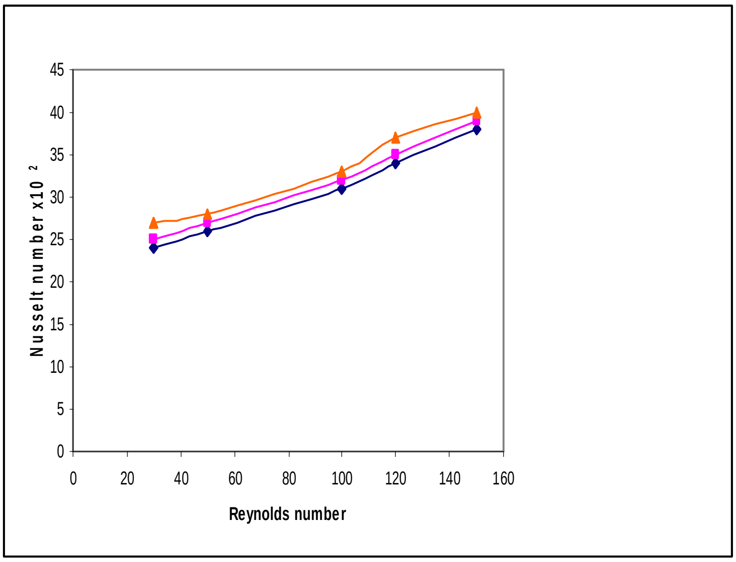


(b)

Figure (9) Liquid Reynolds number as function of Nusselt number different gas flow rates
a-**For falling film** **b- bubble column**



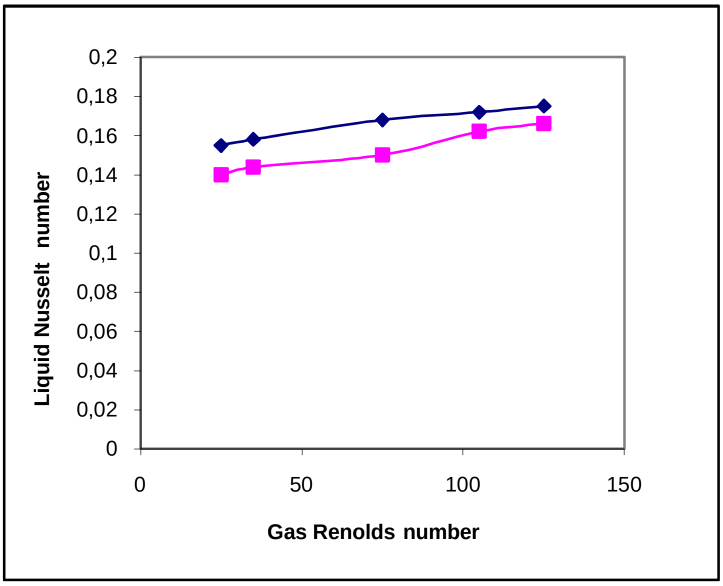
(a)



(b)

Figure (10) Gas Reynolds number as function of liquid Sherwood number with different liquid concentrations for Liquid flow = 0.3 kg /min.
a-For falling film b- bubble column

(a)



(b)

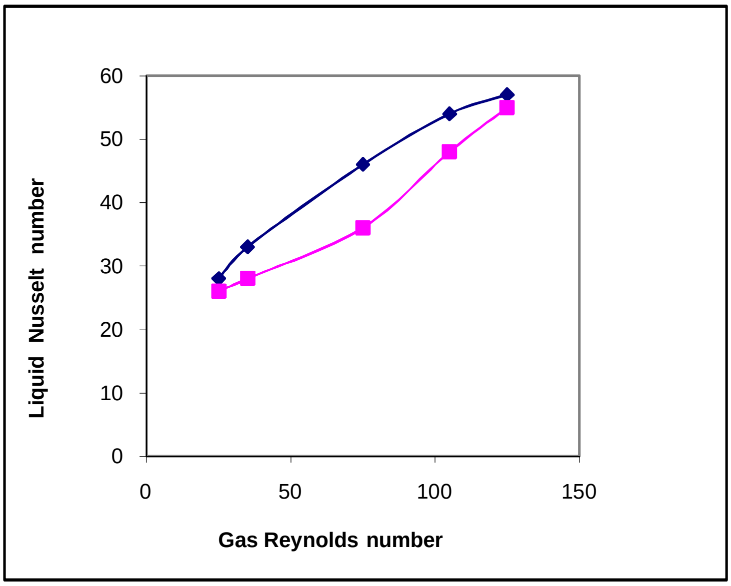


Figure (11) Gas Reynolds number as a function of liquid Nusselt number with different liquid concentrations , liquid flow = 0.3 kg / min.
a-for falling film . b- for Bubble column.