EFFECT OF PHYSICAL PROPERTIES ON HEAT TRANSFER AND FLOW REGIMES IN BUBBLE COLUMNS

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Received 11 May 2014 Accepted 25 March 2015

ABSTRACT

This work discusses the effect of superficial gas velocity and liquid properties (viscosity μ, surface tension σ, thermal conductivity k , density ρ , specific heat C_p) on the heat transfer coefficient and gas holdup investigated in a bubble column. Experiments were carried out in a Plexiglass column (0.15 m diameter and 1.5 m height). A perforated plate was used as a gas distributor, having 84 holes of 1mm diameter, and 0.37% opening area. The heat transfer coefficient was measured for the air-liquid systems in bubble column of four types of liquid (water, 60%ethanol, 35% glycerol, and 65% glycerol) covering a range of surface tension and viscosity values, while the gas phase is atmospheric air. The superficial gas velocity, U_G, was varied in rang of (0.0037-0.094) m/sec. For all sets of experiments the height of liquid phase was maintained constant at 0.8 m above the gas distributor. From experimental, data it is found that the values heat transfer coefficient for aqueous glycerol solutions decrease with increasing concentration of glycerin and are lower than those for 60%ethanol and water solutions. This is attributed to the combined effects of surface tension, viscosity, specific heat, and thermal conductivity of the liquid. The overall gas holdup for all liquids increases with an increase in superficial gas velocity, the liquid property has an impact on gas holdup. An increase in liquid viscosity results in large bubbles and thus higher bubble rising velocities and lower gas holdup. A correlation based on dimensionless groups for the prediction of heat transfer coefficient is proposed and found to be in good agreement with available data.
Keywords: heat transfer coefficient; liquid properties; bubble column.

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تأثير الخواص الفيزيائية على انتقال الحرارة وانظمة التدفق في الاعمدة الفقاعية

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الخلاصة

يناقش هذا البحث تأثير سرعة الغاز السطحية وخواص السائل (اللزوجة μ, الشد السطحي σ, الموصلية الحرارية, الكثافة ρ, السعة الحراريه c_p) على معامل انتقال الحرارة وتعطيل الغاز (الغاز المحتجز) في العمود الفقاعي.التجارب نفذت في عمود زجاجي قطره (0.15 م)وارتفاعه (1.5 م) والموزع الغازي عبارة عن صفيحة مثقبة تتكون من 84 فتحة كل منها بقطر 1 ملم ونسبة 0.37 المساحة المفتوحة. تم قياس معامل انتقال الحرارة للأنظمة غاز-سائل في العمود الفقاعي لأربع أنواع من السوائل

(ماء, 60%ايثانول, 35%كليسيرول, 65%كليسيرول) حيث تم تغطية مدى من اللزوجة والشد السطحي,بينما المرحلة الغازية تتمثل بالهواء الجوي. سرعة الغاز السطحية u_G تتغير من (0.094-0.0037)م/ثانية. في جميع التجارب يكون ارتفاع السائل ثابت 0.8م فوق موزع الغاز. ولقد وجد من خلال التجارب ان معامل انتقال الحرارة لمحاليل الكليسيرين يقل بزيادة تركيز الكليسيرين وهو اقل من معامل انتقال الحرارة في محاليل 60%ايثانول والماء. ويعزى ذلك الى التأثير المشترك لكل من الشد السطحي, اللزوجة, السعة الحرارية والتوصيل الحراري للسائل.تعطيل الغاز (الغاز المحتجز) الكلي لجميع السوائل يزداد بزيادة سرعة الغاز السطحية.خواص السائل له تأثير على تعطيل الغاز (الغاز المحتجز) حيث ان الزيادة في لزوجة السائل تؤدي الى تكوين فقاعات غازية كبيرة والتي تكون ذات سرعة عالية وبالتالي فأن تعطيل الغاز (الغاز المحتجز) يقل. ولقد تم استنتاج معادلة عملية لحساب معامل انتقال الحرارة والتي تتفق بصورة جيدة مع البيانات العملية المتوفرة.

Nomenclature

A	heat transfer area	m^2
C_P	specific heat	$J/k_g.K$
D	diameter of the column	m
g	gravitational acceleration	m/s^2
h_w	heat transfer coefficient	$kW/m^2.K$
H	liquid height of the column	m
I	electric current	A
k	Thermal conductivity	W/m.K
q	heat flow rate	kW
T	temperature	^0C
T_b	bed temperature	^0C
T_L	liquid temperature	^0C
T_{ref}	reference temperature	^0C
T_S	surface temperature	^0C
U_G	superficial gas velocity	m/s
V	voltage	V

Greek

μ	dynamic viscosity	$p_a.s$
ρ	density of water	k_g/m^3
σ	surface tension	J/m^2
ε_G	overall gas holdup	---

INTRODUCTION

The bubble column is regarded as one of the most important multiphase flow systems. It is widely used in many industrial applications including chemical, biochemical, petrochemical, environmental and metallurgical processes, **Balasim et al. [1].** Examples of such chemical and petrochemical processes are partial oxidation of ethylene to acetaldehyde, wet-air oxidation, methanol synthesis, and hydrogenation of organic liquids. In biochemical industries bubble columns are used for cultivation of bacteria, cultivation of mold fungi and treatment of sewage. In metallurgical industries, it can be used for leaching of ores, **Rahman [2].**

The industrial importance of bubble columns remains undisputed mainly due to the advantages that it offers from absence of moving parts, leading to easier maintenance, simple construction, high effective interfacial area, the continuous phase is well mixed, a relatively low pressure drop, good temperature control, excellent heat rate caused by strong gas-liquid interactions, and reasonable inter-phase mass transfer rates at low energy input required for operation, **Anil [3].**

Design and scale-up of bubble columns remain challenging tasks due to the complexity of their non-linear hydrodynamics and phases interactions, **Rahman et al. [4].** Thermal control in bubble columns is of importance since in many chemical and biochemical processes, chemical reactions are usually accompanied by heat supply (endothermic) or removal (exothermic) operation. Therefore, maintaining desirable bulk media temperature is necessary which plays an important role in the performance of the reactor ,**Nigar et al. [5].** Consequently such reactors are equipped with heat exchangers immersed in the main reactor to control the heat of reaction. Reactor walls may also be employed for this purpose, **Khalid [6].** The knowledge and understanding of heat transfer phenomena in bubble columns and quantifying the heat transfer rates and coefficients are important since they are required for proper, safe and efficient design and operation of these reactors, **Rahman et al. [4]**. As mentioned earlier, one attractive feature and main characteristics for the wide applications of BCs is the high heat transfer rate, where the heat transfer rate in gas-liquid flow of bubble columns is reported to be 100 times greater than in single phase (gas phase) flow for the same flow rates with respect to column cross section, **Rahman [2].**

High heat transfer rate is one of the important characteristics in the operation of bubble column. This rate is influenced by a number of physical parameters and operating conditions. gas-holdup , superficial gas velocity, circulation velocity and physical properties of liquid, all these factors are highly interactive and control the bubble column performance, **Khalid [6].**

Bubble columns are used in a variety of processes as an apparatus to achieve mass transfer and/or chemical reaction, usually in low viscosity system. In the last two decades, bubble columns have found widespread application in biotechnological processes such as the production of baker's yeast, wastewater treatment, single-cell protein production, and citric acid fermentation etc. of the high viscosity systems, **Khalid [6].**

Experimental investigations on bubble columns are performed with pure water and few for liquids more viscous than water. There is a lack of knowledge about the effect of liquid properties on the heat transfer process and thus, on gas holdup in bubble columns. The purpose of this work is to study the effect of liquid properties on heat transfer coefficient in a bubble column. Various liquids covering a range of surface tension and viscosity values are employed, while atmospheric air is used as the gas phase for all experiments. A new correlation is proposed for the prediction of heat transfer coefficient.

EXPERIMENTAL SECTION

Experiments were conducted in a large-scale grid of Plexi glass column of 0.15 m internal diameter and height 1.5 m as shown in **Figure (1).** The top of the column is opened to the atmosphere. The column was supported by rigid metallic structure to keep it vertical and to minimize the mechanical vibrations which might affect the measured heat transfer signals. Oil-free compressed air constituted the gas phase, while (tap water, 60% ethanol, 35% glycerol, 65% glycerol) were used as the liquids phase, **Table (1)** gives the liquid phase used in this work together with their physical properties. The experiments were conducted in a semi-batch mode; continuous in relation to the gas flow and batch with reference to the liquid flow. Gas flow was supplied by compressor; the flow rate of air was adjusted by rotameters system, consisting of two rotameters connected in parallel to increase gas velocity range. The superficial gas velocity was varied in the range of (0.0019 to 0.094) m/s which cover both bubbly and churn-turbulent flow regimes. Air was introduced into the column through a perforated stainless-steel plate of 3 mm thickness which had 84 holes, with a diameter of 1 mm and 0.37% opening area, a conical shape reducer was installed for the purpose of minimizing the fluctuation of the gas phase.

Heat was supplied to the gas-liquid dispersion in the bubble column from the electrically heated heat transfer section. The heater assembly is shown in **Figure (2),** which was installed vertically at 0.3 m above the distributor as a heat source in the immersed heater-to-bed system with 0.012 m diameter by 0.5 m length, 1000 W/ 220V electric heating U shaped elements. The power consumed by the heater was controlled by means of variac transformer to give 577.5 W for different surface heater and bulk temperatures. A clamp meter was used also to measure the power directly for more accurate results.

Five thermocouple sensors of K-type were used to sense the temperature in bubble column, two thermocouples at the heat transfer surface element were used to measure the surface temperature of the heating element (Ts), three thermocouples are used to measure the temperature in the bed at different height in bubble column, and the average bed temperature is (Tb). All thermocouples are connected to the data acquisition system (interface) which can be defined as an electronic circuit which enables the communication between the system under study and the computer to take advantage of the computer software for generating reports, plots, etc ….

A temperature measuring interface unit was built to measure the temperature from five type (k) thermocouples, the interface was connected to the computer and can be calibrated and controlled via visual basic 6.0 application software written especially for this purpose, the measured temperature from each sensor was exported to a text file plus the measuring time for further analysis. The interface scanning rate was fixed to be 1 second between each sensor reading, so that, each sensor would be scanned every 8 second. A type K transducer was connected inside the unit case for each thermocouple, each transducer was calibrated by an equivalent electronic circuit inside it to the reference point at 0°C, and the output for each transducer was designed according to the following equation **[7].**

$$V = 1.0(T - T_{ref}) \tag{1}$$

Where Voutput in mV and the temperature was measured in °C, Tref. was fixed to be 0°C, V was designed to be 0.1 mv for each 1 °C difference. At 0°C, the transducer output would be 0 mV. Hence, at 100°C the transducer output voltage is equal to 100 mv. The transducer signal was then converted to a digital signal using an analog – to – digital converter and transferred directly to the computer via the printer port.

Any deviation from the designed output voltage can be handled by the program. This can be achieved by immersing all thermocouples in a steady – state constant bath temperature and monitor the deviation in order to sense the deviation which normally should be in the order of ± 3°C.

The heat transfer coefficient hw was calculated by dividing the heat rate by the heating surface area and the temperature difference between the heating surface and bulk liquid temperatures, assuming quasi-steady-state condition **[8].**

$$h_W \frac{\frac{q}{A}}{T_{s-T_b}} \tag{2}$$

RESULTS AND DISCUSSION

In this study, the heat transfer coefficients in air-water, air-60% ethanol, air-35% glycerol and air-65% glycerol systems were investigated

1. Effect of superficial gas velocity

1-1 Effect of superficial gas velocity on heat transfer coefficient

The effects of superficial gas velocity were investigated for different air-liquid systems. Figures 3 (a, b, c and d) show the heat transfer in air-water, air-60% ethanol, air-35% glycerine, and air-65% glycerine versus superficial gas velocity.

It can be seen that the strong influence of the superficial gas velocity on the heat transfer coefficient for all air-liquid system between the bubbly and churn-turbulent flow regimes.

Heat transfer coefficients increase with an increase of gas velocity, irrespective liquid viscosity. These results also showed that the rate of increase of heat transfer coefficients with gas velocity was rapid at low gas velocity (bubbly flow regime), This must be related to the fact that at low superficial gas velocity the small bubble sizes are formed and almost uniformly distributed throughout the whole column area, the bubbles rise almost vertically with the same speed and without coalescence drifting an amount of liquid to the top of the column ,by further increasing in the gas flow rates the increase in heat transfer coefficient become smaller with in the churn-

turbulent flow regime this related to that when the superficial gas velocity increased continued the significant gas transport occurs through the large bubbles formed by coalescence begin to rise resulting in a kind of churn-turbulent flow pattern which cause slow down in heat transfer coefficient. This is in agreement with the observations of **(Rahman [2], Nigar et al. [5], Khalid [6],Ola [12], Hanning [13]).**
Figure (4) from **Chen et al. [16]** depicts approximate flow structure observed with increasing gas flow. The dispersed bubble flow regime (I) is characterized by nearly uniform bubble size and radially uniform gas holdup. This is followed by transition regime (II) when increasing gas velocity generates more bubbles leading to increased bubbles interactions and growth in bubble size. The larger bubble stream is seen moving through column center where the heat transfer rate is expected to increase. With further increase in gas velocity, coalesced bubble flow (or heterogeneous) regime (III) is reached where fast moving large coalesced bubbles begin to emerge due to combined effect of higher initial bubble size and faster coalescence rate, **Anil [3].**

1-2 Effect of superficial gas velocity on gas holdup

Gas holdup (ε_G) is one of the most important parameters in bubble columns; it is basically defined as the reactor dynamic volume occupied by the gas or the volume fraction of gas phase occupied by the gas bubbles, likewise it is possible to characterize the liquid phase holdup as the volume fraction of liquid**,(Rahman [2], Khalid [6], Maedeh and Faramarz [17],and Behnoosh et al. [18]).**
The direct visual observation for the measurements of the total gas holdup; is determined from the knowledge of slumped liquid-phase column height (H_s) when the gas flow through the liquid is zero (static height), and the expanded height or dynamic height (H_e) of the two-phase gas liquid suspension corresponding to a particular value of the superficial gas velocity (U_G), and the following relation, **Rahman [2]:**

$$\varepsilon_G = \frac{H_e - H_s}{H_e} \tag{3}$$

Gas hold up depends mainly on the superficial gas velocity. In this study the gas hold up have been measured at different superficial gas velocity, the results are shown in **Figure (5).** All the experiences show the positive effect of superficial gas velocity on gas hold up. This positive effect has been shown in the most published studies, **(Rahman [2], Nigar et al. [5], Khalid [6], Hanning[15], Maedeh and Faramarz [17],Behnoosh et al. [18] ,and Boris [19]).** The gas holdup would increase linearly with the gas flow rate (superficial gas velocity). In the homogeneous regime (bubbly flow regimes), the bubble size is small and uniform and bubble travel upwards in a helical path without any major collision or coalescence, as the gas flow rat increases the hindrance progressively reduces the bubble velocity leading to a further increase of the gas holdup. The opposite holds true for the heterogeneous regime, at high superficial gas velocity all the bubbles will be large. The large bubbles have higher rise velocity than small bubbles, therefore residence time of large bubbles decrease and cause to decrease rate of increasing gas hold up.

2. Effect of liquid properties

2-1 Effect of liquid properties on gas holdup

The liquid phase property has an impact on bubble formation and/or coalescing tendencies and hence is an important factor affecting gas holdup, **Nigar et al. [5].** The liquid properties which are most important are the surface tension and the viscosity of the medium, **Heijnen and Riet [20].** **Figure (6)** the data are plotted in terms of gas holdup versus gas phase superficial velocity for air–

60% ethanol, air–water, air–35% glycerine and air–65% glycerine systems. As it is expected, gas holdup increases with gas flow rate.

As shown in **Figure (6)** a slight increase in gas holdup values is observed when the lower surface tension ethanol solution is used as liquid phase. Compared to water, the surface tension is the only physical property which differs significantly from water. The effect of surface tension on gas holdup can be qualitatively described in that a lower surface tension gives a lower bubble rise velocity and therefore a higher holdup, **Heijnen and Riet [20].**

It is also evident from **Figure (6)** that the influence of ethanol is bigger for high air flow rates. In these conditions, collision between air bubbles is more intense and bubbles coalescence becomes increasingly significant, the surface tension being a major influence on this process. At low air flow rates, the liquid-phase surface tension has little effect on gas holdup. The amount of air into the reactor is small and the coalescence is not significant. So, the inhibition of coalescence by ethanol is not high enough to be relevant, **Carla and Jose [21].**

Also gas holdup is very dependant on the viscosity of liquid, **Auroba[22]. Figure (6)** refers to strong influence of glycerine concentration on the gas holdup. Thus, as the concentration of glycerine solution was increased, the mean gas holdup value decreased in the bubble column, or in other words. It was found that the gas hold up value decreases with increasing liquid viscosity. Therefore, the decrease in gas holdup values may be attributed to: Increasing of the system viscosity and Formation of large bubbles with fast rising velocity, **Khalid [6]** .

2-2 Effect of liquid properties on heat transfer coefficient

The physical properties of any liquid used in a bubble column will be determined its hydrodynamic behavior and then the rate of heat and mass transfer. **Lewis et al. [23]** pointed to the importance of the distinguishing between the low viscosity and high viscosity systems, because of the hydrodynamic behavior is not the same. Therefore, the liquid viscosity, surface tension and liquid density in the end determine the extent of liquid circulation and then the amount of heat transfer rate, **(Hikita et al.[24].**

The effects of liquid properties were investigated for different air-liquid systems. **Figures (7)** show the heat transfer coefficient in air-water, air-60% ethanol, air-35% glycerine, and air-65% glycerine versus superficial gas velocity.

The heat transfer coefficient hw for water, 60% ethanol, 35% glycerine and 65% glycerine are shown in **Figure (7).** As can be seen in this figure, the heat transfer coefficient for 60% ethanol lower than those for water, These results may be attributed to the combined effect of surface tension, specific heat and thermal conductivity of the liquids (water, 60% ethanol) when the rest of properties is approximate the same. This mine heat transfer coefficient rises with an increase in heat capacity, and thermal conductivity of the liquid, **Chengtian [25].** The heat transfer coefficient also increses with increases surface tension, this may be attributing to the decrease of the liquid surface tension, reduce the bubble coalescence rate but increase the bubble breakup rate, which causes the reduction of the bubble size. Furthermore, the decrease in bubble size obviously decreases the heat transfer coefficient. The effect of density and viscosity can be neglected.

Figure (7) also presents the heat transfer coefficient values obtained for 35% glycerine and 65% glycerine. It can be seen that in the figure at the same superficial gas velocity, the heat transfer coefficient decrease with increasing concentration of glycerine solution. On the other hand, the heat transfer coefficients for all highly viscous liquid of glycerine solutions are considerably lower than that for air-water system under the same operating conditions. This may be explained on the basis of the effect of increasing liquid viscosity of the liquids when the effected of the rest of properties is approximate the same and can be neglected. Heat transfer coefficient decreases with increasing liquid viscosity in multiphase reactors. The decrease in heat transfer rate has been attributed to increase in thermal boundary sub-layer thickness of laminar flow around the heating surface with increasing viscosity due to decrease in turbulence and increase in viscous friction loss between the phases - thus increasing resistance for conduction heat transfer **Anil [3].**

3- Correlation

As described above, the conceivable factors affecting heat transfer coefficient hw are considered to be the superficial gas velocity uG, the liquid specific heat cp, the liquid thermal conductivity k, the liquid density ρ, the liquid viscosity μ, the liquid surface tension σ, and the gravitational constant g. For the present problem the gas properties were not taken into account in obtaining the general correlation.

The dimensional analysis and the least-square method were applied to all the experimental data. The final correlation for the heat transfer coefficient hw is given by:

$$\frac{h_w}{\rho c_p u_G}\left(\frac{c_p \mu}{k}\right)^{2/3} = 5.451\left(\frac{u_G \mu}{\sigma}\right)^{-0.655}\left(\frac{\mu^4 g}{\rho \sigma^3}\right)^{0.334} \qquad (4)$$

Figure (8) shows the comparison of the observed and calculated values of the Stanton number hw/ρcpuG. In this Figure, the Stanton numbers observed in the present work are plotted against the Stanton numbers calculated from **eq. (4).** The observed Stanton numbers are in good agreement with the calculated ones with an average deviation for (water, 60% ethanol, 35% glycerine, 65% glycerine) are (0.73%, 2.8%, 1.4%, 0.9%) and a maximum deviation (2.8%, 9.2%, 2.2%, 1.6%) respectively

If the effect of liquid surface tension on the heat transfer coefficient hw value is ignored, we finally obtain the following correlation:

$$\frac{h_w}{\rho c_p u_G}\left(\frac{c_p \mu}{k}\right)^{2/3} = 0.294\left(\frac{u_G^{\,3} \rho}{\mu g}\right)^{-0.277} \qquad (5)$$

Figure (9) compares the measured values of the Stanton number with those calculated from equation (5). Although the measured values of the Stanton number are in agreement with the calculated ones with an average deviation for (water, 60% ethanol, 35% glycerine, 65% glycerine) are (2.8%, 4.6%, 0.5 %, 3.9%) and a maximum deviation (11.2%, 11.7%, 1.21%, 12.7%) respectively, the data points show the systematic error for the data of a few specified systems and display somewhat greater scattering than shown in **Figure (9),** indicating that the effect of the liquid surface tension on the hw value cannot be denied

Figure (10) shows the comparison of the heat transfer coefficient by experimental work with published correlation predictions**,(Hart [26]; Nishikawa and Hashimoto[27]; Deckwer [28]; Hikita et al. [24]; Kawase and Moo-Young [29]; Verma [30]; Kawase and kumagai [31]; and Yang et al. [32])**. the measured values of the Stanton number are in agreement with the calculated ones with an average deviation (5.5%, 4.6%, 5.57%, 3.21%, 5.86%, 5.15%, 5.6%, 6.23%) and a maximum deviation (20.8%, 20.3%, 20.6%, 14.4%, 21.5%, 19.4%, 20.9%, 21.8%) respectively. Therefore the results have shown a good agreement between the experimental measurements and **Hikita et al.[27]** correlation for heat transfer coefficients. However, the measured of other investigations are shown in **Figure (10)** varies from those obtained in this work. This would be attributed to many uncertainties caused by different measurement techniques (probe) used, different operating and design conditions applied in these reported studies and different liquid properties between this work and previous investigations which effect on the hydrodynamic behavior of liquid.

CONCLUSION

The heat transfer coefficient measurements are obtained in different air-liquid systems of a two phase bubble column based on constant heat flux, over a wide range of liquid properties and superficial gas velocities. it can generally be concluded that the heat transfer coefficients increas with an increase in the superficial gas velocity, the increase is rapid in the beginning (bubbly flow regime), but slows as the superficial gas velocity is increased (churn-turbulent flow regime).

The heat transfer coefficient for 60% ethanol lower than those for water. These results may be attributed to the combined effect of surface tension, specific heat and thermal conductivity of the liquids (water, 60% ethanol) when the rest of properties is approximate the same. This mine heat transfer coefficient rises with an increase in heat capacity, and thermal conductivity of the liquid. The heat transfer coefficient also increases with increases surface tension, this may be attributing to the decrease of the liquid surface tension, reduce the bubble coalescence rate but increase the bubble breakup rate, which causes the reduction of the bubble size. Furthermore, the decrease in bubble size obviously decreases the heat transfer coefficient.

The heat transfer coefficient for 35% glycerol and 65% glycerol decrease with increasing concentration of glycerin solution. On the other hand, the heat transfer coefficients for all highly viscous liquid of glycerine solutions are considerably lower than that for air-water system under the same operating conditions. This may be explained on the basis of the effect of increasing liquid viscosity of the liquids when the effected of the rest of properties is approximate the same and can be neglected. Heat transfer coefficient decreases with increasing liquid viscosity in multiphase reactors.

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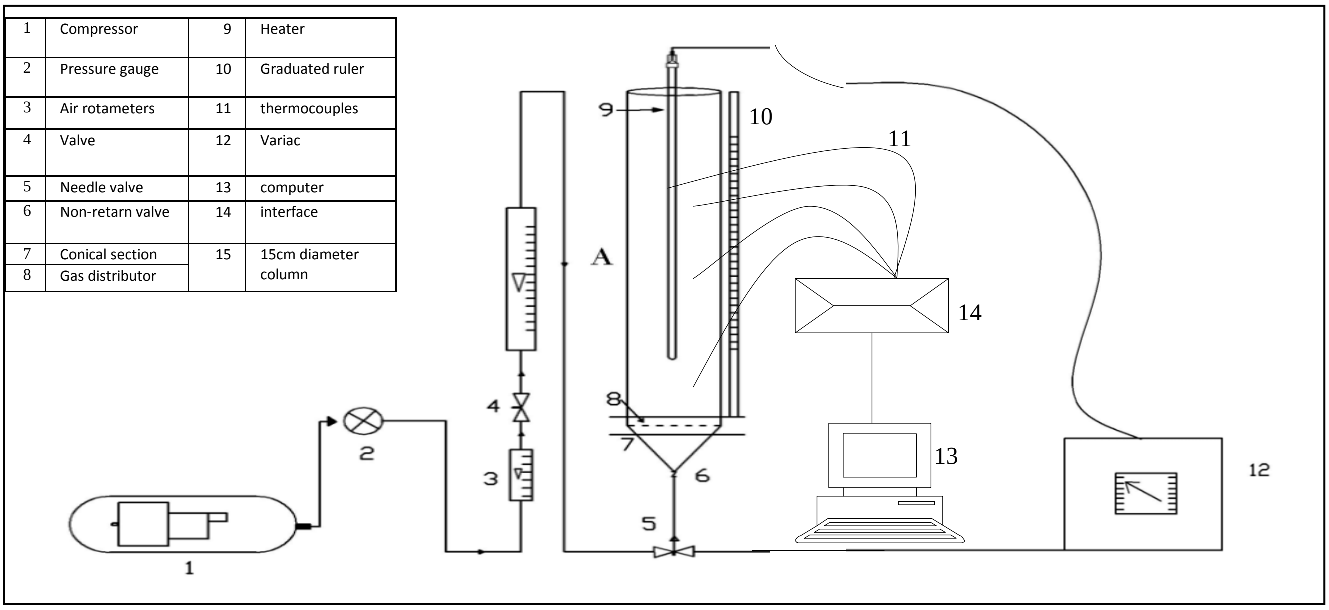
Table (1): physical properties of liquids used, (Celsius[9] , Gonzalo et al. [10], Coker[11] ,Glycerine[12], Don.and Perry [13])

Liquid	T_L, ºC	$\mu \times 10^3$, Pa s	$\rho \times 10^{-3}$ Kg/m^3	Cp $\times 10^{-3}$ J/kg K	k, W/m K	$\sigma \times 10^3$ J/m^2
60 wt% ethanol	20	1.079 [9]	0.862 [9]	3.059 [9]	0.213 [9]	26.72 [10]
	30	0.876 [9]	0.854 [9]	3.159 [9]	0.210 [9]	25.81 [10]
	40	0.722 [9]	0.846 [9]	3.258 [9]	0.207 [9]	24.97 [10]
	50	0.604 [9]	0.838 [9]	3.357 [9]	0.204 [9]	24.11 [10]
Water	20	1.029 [11]	1.032 [11]	4.204 [11]	0.599 [11]	74.60 [11]
	30	0.817 [11]	1.023 [11]	4.191 [11]	0.613 [11]	72.58 [11]
	40	0.665 [11]	1.013 [11]	4.181 [11]	0.625 [11]	70.57 [11]
	50	0.553 [11]	1.004 [11]	4.175 [11]	0.635 [11]	68.55 [11]
	60	0.468 [11]	0.994 [11]	4.171 [11]	0.645 [11]	66.53 [11]
	70	0.403 [11]	0.985 [11]	4.172 [11]	0.654 [11]	64.50 [11]
35 wt% glycerol	20	3.122 [12]	1.086 [12]	3.645 [13]	0.464 [12]	69.89 [12]
	30	2.303 [12]	1.081 [12]	3.623 [13]	0.477 [12]	68.65 [12]
	40	1.771 [12]	1.076 [12]	3.602 [13]	0.485 [12]	67.36 [12]
	50	1.394 [12]	1.058 [12]	3.581 [13]	0.494 [12]	66.06 [12]
	60	1.131 [12]	1.052 [12]	3.558 [13]	0.502 [12]	64.70 [12]
	70	0.955 [12]	1.047 [12]	3.528 [13]	0.510 [12]	63.23 [12]
65 wt% glycerol	20	15.73 [12]	1.168 [12]	3.115 [13]	0.362 [12]	67.17 [12]
	30	10.16 [12]	1.162 [12]	3.103 [13]	0.367 [12]	66.28 [12]
	40	6.999 [12]	1.156 [12]	3.090 [13]	0.371 [12]	65.36 [12]
	50	5.021 [12]	1.151 [12]	3.077 [13]	0.371 [12]	64.35 [12]
	60	3.752 [12]	1.144 [12]	3.064 [13]	0.375 [12]	63.30 [12]
	70	2.978 [12]	1.138 [12]	3.052 [13]	0.379 [12]	62.14 [12]



1	Compressor	9	Heater
2	Pressure gauge	10	Graduated ruler
3	Air rotameters	11	thermocouples
4	Valve	12	Variac
5	Needle valve	13	computer
6	Non-retarn valve	14	interface
7	Conical section	15	15cm diameter column
8	Gas distributor		

Figure (1): Schematic diagram of the experimental apparatus

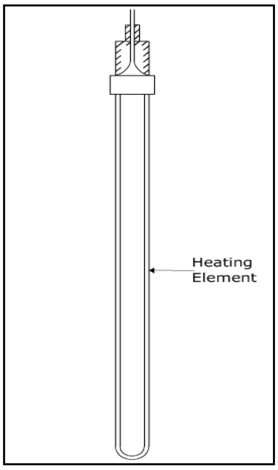
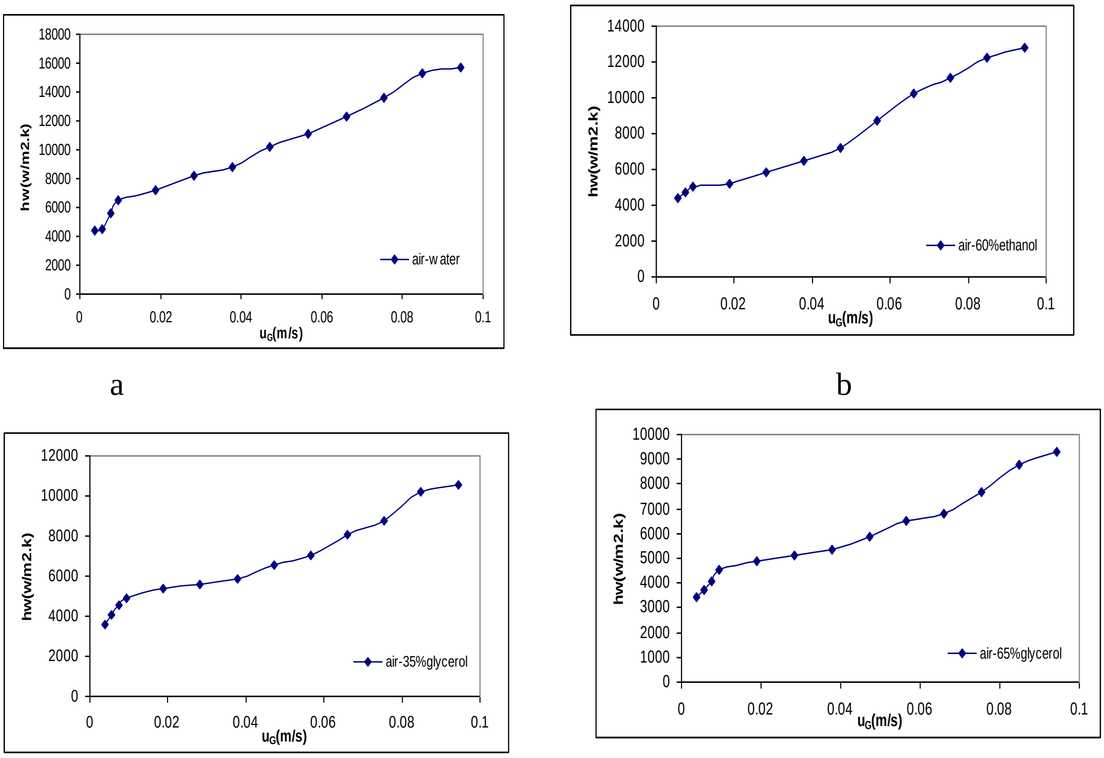


Figure (2): schematic diagram of the heater



a

b

c

d

Figure (3): Effect of superficial gas velocity on heat transfer coefficient for a) water b) 60%ethanol, c) 35%glycerol, c) 65%glycerol

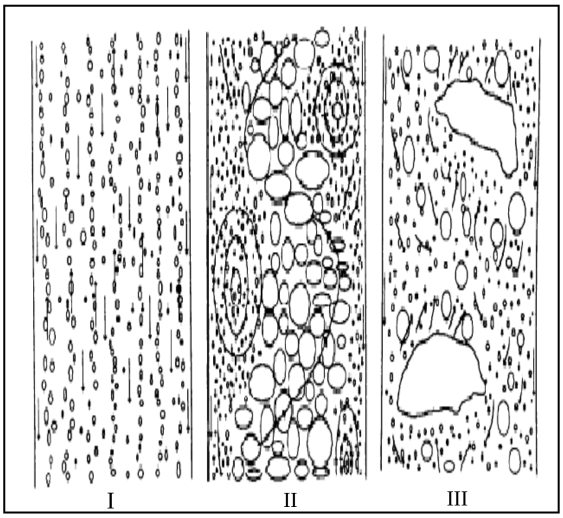
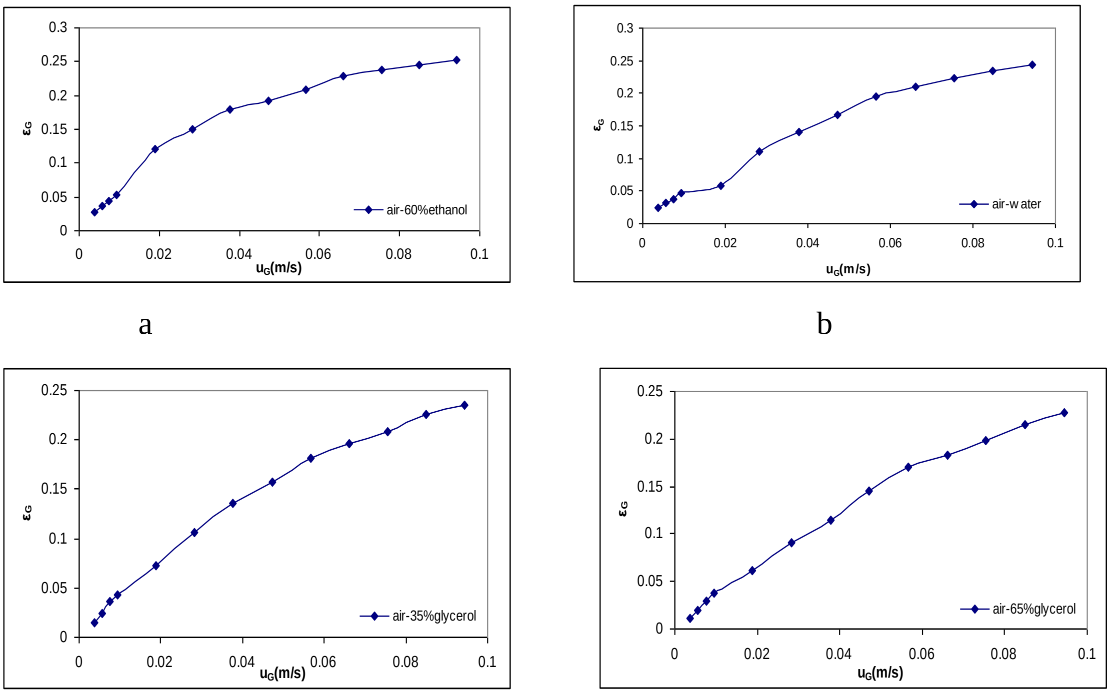


Figure (4): Flow regimes in 3-D bubble column (Chen et al.[14]).



a b

c d

Figure (5): shows the dependence of gas holdup on corresponding gas superficial velocity for air–60%ethanol, air–water, air–35% glycerol and air–65% glycerol systems .

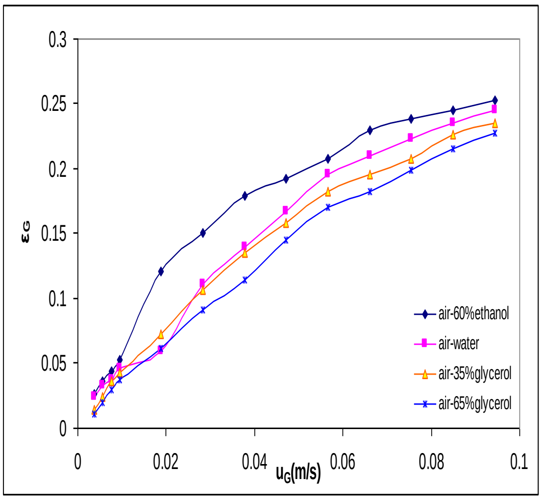


Figure (6): shows the effect of liquid properties on gas holdup for air–60%ethanol, air–water, air–35% glycerol and air–65% glycerol systems .

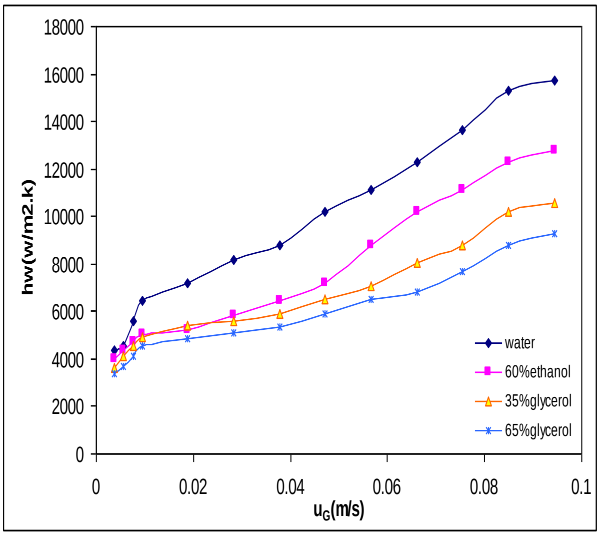


Figure (7): shows the effect of liquid properties on heat transfer coefficient for air–water, air–60%ethanol, air–35% glycerol and air–65% glycerol systems .

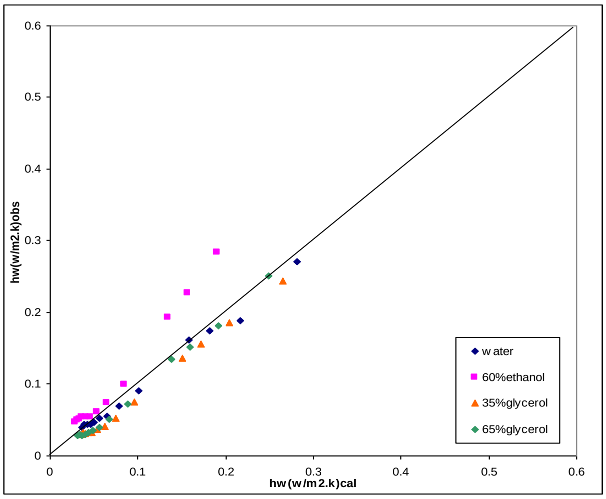


Figure (8): shows the comparison of the observed and calculated values of the Stanton number $h_w/\rho c_p u_G$.

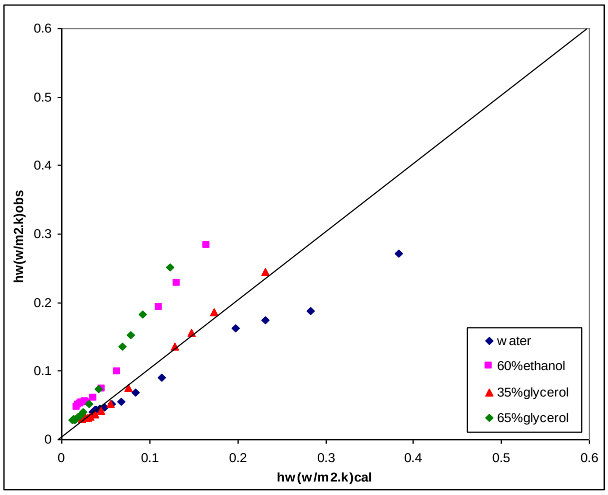


Figure (9): shows the comparison of the observed and calculated values of the Stanton number $h_w/\rho c_p u_G$.

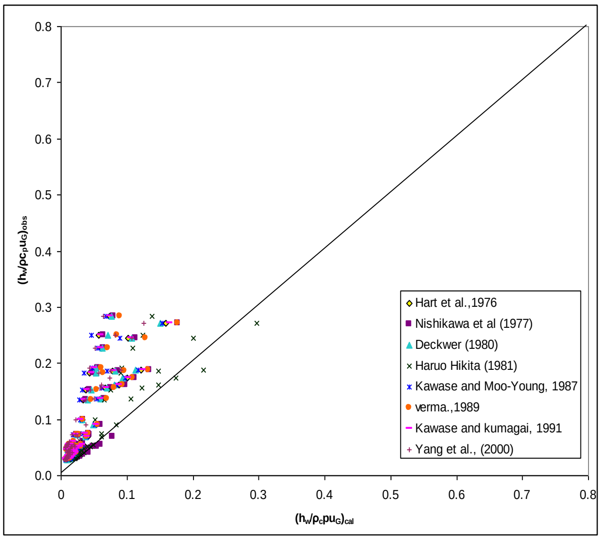


Figure (10): shows the comparison of the heat transfer coefficient by experimental work with published correlation predictions