Hydrodynamics in a Trickle Bed Reactor

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Received on: 10/5/2012 & Accepted on: 9/5/2013

ABSTRACT

Experimental investigations have been carried out to study the performance of trickle bed reactor. The effect of key parameters that play predominate role in the performance of trickle bed reactor was studied. A laboratory unit was constructed for this purpose where a versatile reactor setup required " high pressure stainless steel reactor of 0.05m i.d × 1.25m height", in which the hydrodynamic experiments carried out under different operating condition namely, superficial gas velocity and liquid velocity , reactor pressure, bed temperature .Air–water system was used for hydrodynamic experiments pressure drop, dynamic liquid holdup, and axial dispersion coefficients were estimated. The results also show that the dynamic liquid holdup increases with increasing liquid velocity and decreases with increasing superficial gas velocity and bed temperature. Axial dispersion tends to increase with increasing superficial gas and liquid velocities while it decreases with increasing bed temperature.

Keywords:Hydrodynamic,Trickle bed reacctor, Axial dispersion , Pressure drop , Dynamic liquid holdup

دراسة عملية لهايدرودواينمك مفاعل الطبقة الوشلة

الخلاصة

تضمن البحث دراسة عملية لكفاءة أداء عمود الطبقه الوشله Trickle bed Reactor. حيث تم دراسه تاثير المتغيرات الرئيسيه التي تلعب دور اساسي في اداء عمود الطبقة الوشلة. تضمنت الدراسة نصب جهاز مختبري مصنوع من الفولاذ المقاوم للصدأ ذات طول (١,٢٥م) وقطر داخلي (٠,٠٥م) اذ تم اجراء التجارب الهيدرودواينميكية والحركية عند ظروف تشغيلية مختلفة {سرعة الغاز,سرعة السائل , ضغط المفاعل و درجه الحرارة . نظام ماء-هواء قد تم استخدامه في حاله التجارب الهيدروديناميكية تظمنت الدراسه دراسه الانحدار بالضغط (Pressure drop) ونسبه السائل (Liquid holdup) والتفرق المحوري (Axial dispersion) .بينت النتائج العملية عند زيادة معدل جريان السائل يزداد كل من الانحدار في الضغط ,نسبة السائل , والتفرق المحوري,لكن عند زيادة معدل جريان الغاز يزداد كل من الانحدار

https://doi.org/10.30684/etj.31.15A.6
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في الضغط والتفرق المحوري وتقل نسبة السائل . درجة الحراره لها تأثير عكسي على كل من الانحدار في الضغط , نسبة السائل والتفرق المحوري.

NOMENCLATURE

D_{axl}	Dispersion Coefficient	m^2/s	**Greek Symbols**		
dp	Particle diameter	m	ε	Bed voidage	(-)
de	Equivelent diameter	m	ε_{Lt}	Total liquid Holdup(Dynamic+Static)	(-)
G	gravity acceleration	m/s^2	μ	Viscosity	kg/m.s
P	Total pressure (case dependent units)	kPa	ρ_L	Density of liquid	Kg/m^3
ΔP	Pressure drop	kPa	σ_L	Surface tension	N/m
T	Temperature	K	**Dimensionless group**		
u	Superficial velocity	m/s	G_{a_L}	Modified Galileo number	$\frac{\rho_L^2 d_p^2 g \varepsilon^3}{\mu_L^2 (1-\varepsilon)^3}$
Z	Reactor length	m	R_e	Reynolds number	$\frac{\rho\ u\ d_e}{\mu}$
Subscripts					
G	Gas				
L	Liquid				

INTROUDUCTION

Multiphase catalytic processes have been expanding into diverse areas of applications and continue to make a significant impact on the development of new synthetic routes and high-value added products [1].

Three-phase continuous catalytic processes involving gas, liquid and a solid catalyst are widely used in industrial practice including the manufacturing of commodity chemicals. Trickle-bed reactors are the most widely used type of three-phase reactors. The gas and liquid co-currently flow downward over a fixed bed of catalyst particles [2 ,3].The liquid phase flows over the catalyst as a thin film, while the gas phase flows continuously between the catalysts [4]. Trickle-bed reactors are employed in petroleum, petrochemical and chemical industries, in waste treatment and in biochemical and electrochemical processing as well as other application [5] Various flow regimes exist in TBRs depending on the superficial mass velocity, fluid properties and bed characteristics [6,7] such as trickle flow, pulsing flow, mist flow and bubble flow [7]. The performance of a trickle-bed reactor is affected, not only by reaction kinetics, pressure, and temperature, but also by reactor hydrodynamics, which are commonly described by means of global parameters such as pressure drop, liquid holdup, dispersion of gas and liquid phases, catalyst wetting, and mass- and heat-transfer coefficients [8]. Liquid holdup and pressure drop in the bed are the two key hydrodynamic parameters whose knowledge is necessary while designing and scaling up of the reactor [9].

Pressure drop represent the energy dissipated due to fluid flow through the reactor bed, it is important in determining the energy losses, the sizing of

compression equipment, liquid holdup, external contacting efficiency, gas-liquid interfacial area and mass transfer coefficients. The energy dissipation in a gas-liquid concurrent down flow packed bed reactor is due to the frictional losses at the packing surface and the driving forces acting on the liquid flow. Liquid holdup plays an important role in trickle bed reactor hydrodynamic mass and heat transfer; knowledge of liquid holdup is essential for avoiding hot spots and prevent reactor run away. Liquid holdup which partially occupies the void volume of the packed bed is a basic parameter for reactor design because it is related to other important parameters [10]. There are different techniques used for measuring liquid holdup in a laboratory trickle bed reactors at high and atmospheric pressure such as tracer, weighing, electric conductivity, electromagnetic radiation techniques (total liquid holdup) and drainage technique (dynamic holdup) [6,11-14]. Axial mixing represents the degree of flow mixing occurring during the residence time in the reactor. It has also been called axial dispersion, back mixing or longitudinal mixing. This deviation from ideal plug flow behavior has been characterized with the development of the residence time distribution (RTD) technique. [15] were the first of two who studied and described this phenomenon [16].

The present work fouces on the experimental investigation of the hydrodynamic of trickle bed reactor over a porous catalyst particle (0.5Pt/Al2O3) for air-water system.The effect of superficial liquid velocity (0.0013-0.1 m/s), superficial gas velocity (0.018-0.25 m/s) , reactor pressure (0.1- 0.6 Mpa) and bed temperature (25-85 ºC) on the hydrodynamic parameters: pressure drop ,daynamic liquid holdup and axial dispersion coefficient were studied.

EXPERIMENTAL STUDY

Experimental Setup :- A schematic illustration of the experimental facility setup is shown in Figure.1. The experimental rig was made up of stainless steel tube able to withstand temperature up to (140)ºC and pressures up to 4MP with 0.05m inside diameter and 5mm wall thickness packed with (800gm &0.6m height) of catalyst particles. Table1 represents some characteristics of catalyst, pre and post packing, trickle bed reactor and material used through the experiment. The trickle bed reactor was packed with different packing layers of inert particles besides the catalyst layer. A first 0.2m from the top a layer (pre-packing) of 2mm×2mm glass cylinder was set just before the catalyst bed in order to ensure uniform radial liquid distribution over the reactor cross-section, then 0.5%Pt/Al2O3 catalyst particles bed with a height of 0.6m.The last layer (post-packing) again contains 2mm×2mm glass cylinder particles with a height of 0.45m,which supports the catalyst packing to complete a total bed height of (1.25m).The reactor to particle diameter ratio of 31.25 was sufficient to prevent wall effect [17]. The packing was maintained by means of a stainless steel screen placed at the column bottom and had a mesh openings large enough to prevent art factual bed flooding but narrow enough to impede particle crossings. Table(1). Show the bed Characteristics, catalyst specification and operating condition.

To measure the two phase pressure drop through the reactor bed, pressure taps were drilled in the reactor head and in the bottom of the reactor and a differential pressure transducer was mounted. The output signal of the transducer was fed to an A/D converter and stored in PC, with sampling frequency of (250)HZ .The reactor was externally heated with electrical tape heater (Heraeus-Wittmann Gmbh

Heidelberg, type MS6) which was connected to a temperature controller (Yang Ming CX TA 3000) that maintained the bed temperature within ±3ºC of the set point temperature by means of on-off regulator control which manipulated the heat supply of the external heater. For more experimental details find elswhere in [18].

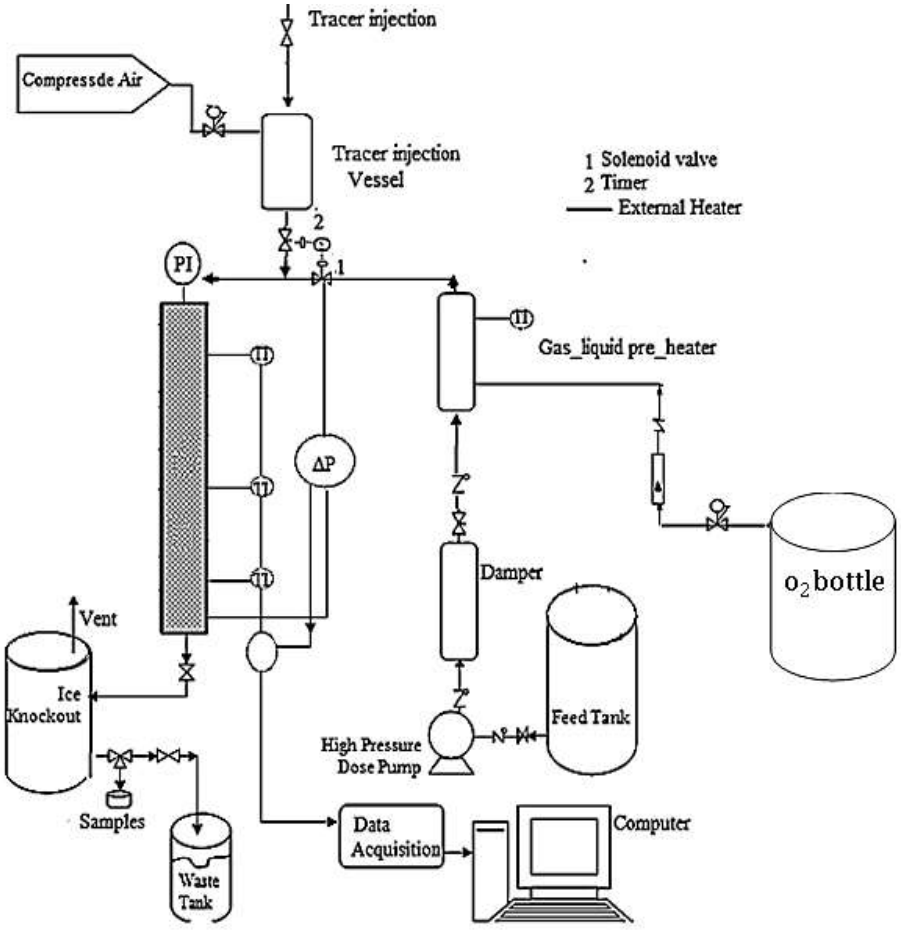


Figure (1) Schematic diagram for the experimental setup.

Table (1) Bed Characteristics, Catalyst Specification and operating condition.

Reactor properties:-		**Catalyst properties**:-	
Reactor diameter (i.d)	0.05 m	Active metal	0.5% pt
Total length	1.25 m	Catalyst support	Alumina
Type of inert bed	Glass Cylinder 3*3 mm	Particle shape	Sphere
Pre packing depth	0.2 m	Particle diameter	0.0016 m
Post packing depth	0.45 m	Surface area	250 m^2/ gm
Bed porosity	0.38-0.4	Pellet density	0.56 gm/cm^3
Pellet porosity	0.52		
Catalyst bed depth	0.6 m		

Operating condition:-	
Bed temperature	25-85 ºC
Pressure	0.1- 0.6 Mpa
Superficial gas velocity	0.018-0.25 m/s
Superficial liquid velocity	0.0013-0.1 m/s

Dye Characteristics	
Type of dye	Reactive red
Commercial name	Forosyn red
Chemical structure	$C_{26}H_{21}N_5Na_4O_{19}S_6$
Molecular weight(gm/gmol)	991.82
Wave length(λ(nm))	485

Experimental Procedure:- After the liquid was heated with an immersed electric heater in the storage tank (100 liter capacity) up to a max of 60°C it was pumped by means of a metering pump (Dose pump, BALDOR FRUM DUTY, USA) to a high pressure small stainless steel tank (Damper, 0.04 id *0.35m length) to damp the pulsation due to pumping. The gas was delivered from a high pressure cylinder equipped with a pressure regulator to adjust the operating pressure. A flow meter coupled with needle valve enabled the gas flow rate to be set and measured. The liquid and gas streams were mixed and preheated in the pre heater before entering the reactor at the top through a distributor containing 29holes (φ=0.5mm) . Discharged fluids (gas and liquid) from the reactor flow through the gas-liquid separator. In the top flange of the separator, stainless steel mesh demister was placed to trap the liquid mist from the effluent gas stream. Pressure indicator and safety valve was mounted to prevent pressure build up in the gas and liquid

delivery and exit streams. One way valve was located in gas and liquid line to assure the flow in one direction.

Tracer Injection System: - A 1.5 L-carbon steel vessel was connected to the top of TBR via an on - off solenoid valve which was energized with time. The system consisted of three valves: two of them being used for injecting the tracer, and pumping air while other is being used for feeding the injection line from a tracer tank to the reactor by means of pumping air through a pulse - type feeding response.

Operating Conditons and Procedures

Experiments were carried out for a range of temperature , pressure, and superficial liquid and gas velocities which covered the trickle flow regime as shown in in Figurexz.2

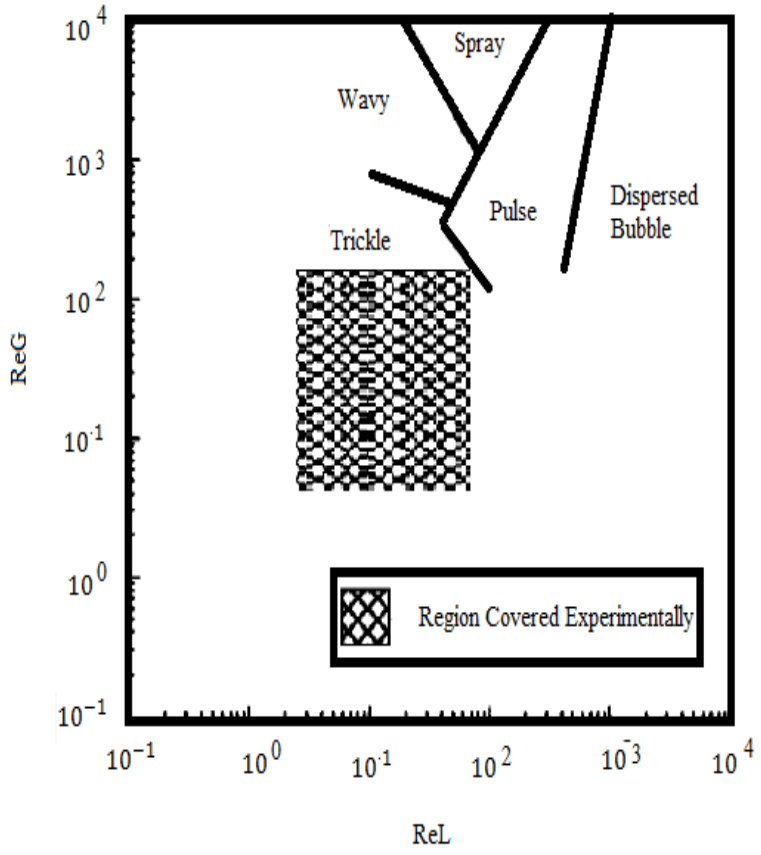


Figure 2. Region of trickle flow covered experimentally in the present study (flow map based on Fukushima and Kusaka [19,20])

Signal Analysises -Pressure drop In the present work, the pressure drop through the bed was measured by using pressure transducers, recording the pressure fluctuations (signals) analysis. Figure (3) shows sample of pressure drop oscillation versus time, increasing proportionally with reactor pressure, superficial gas and liquid velocity while decreasing with temperature. To determine the pressure drop over a period of time, for various signals from recorded sets of data, the average value is calculated.

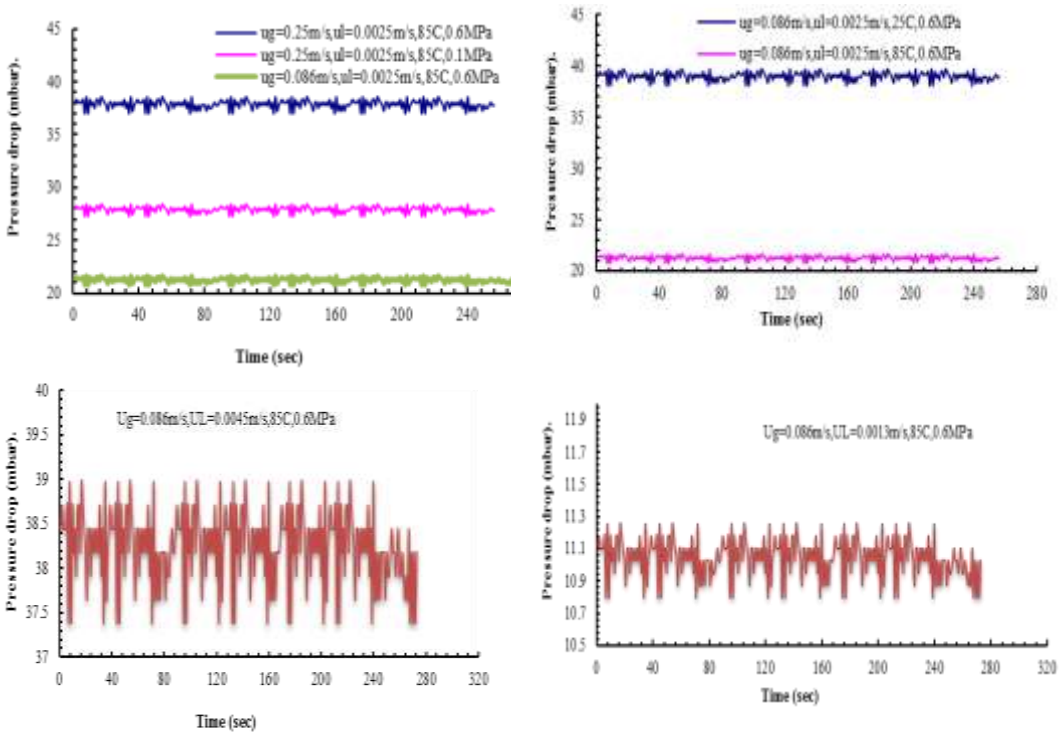


Figure (3) Pressure drop signals at different operating condition.

Liquid holdup and Axial dispersion

The tracer technique, was used to measure the liquid hold up and axial dispersion. Figure (4) depicts a comparison between experimental RTD curves for different sets of temperatures, superficial gas and liquid velocities. By analyzing the curve in Figure (4), some notes can be concluded, 1st as the flow rate increased, the mean residence time of the RTD curve decreased. 2nd, as the liquid velocity increased scanning the selecting range of operating conditions, the RTD curve increasingly deviate from symmetry which means a more back mixing occurred in the liquid phase. 3th, as the temperature increasing caused an increase in mean residence time which leads to low back mixing.

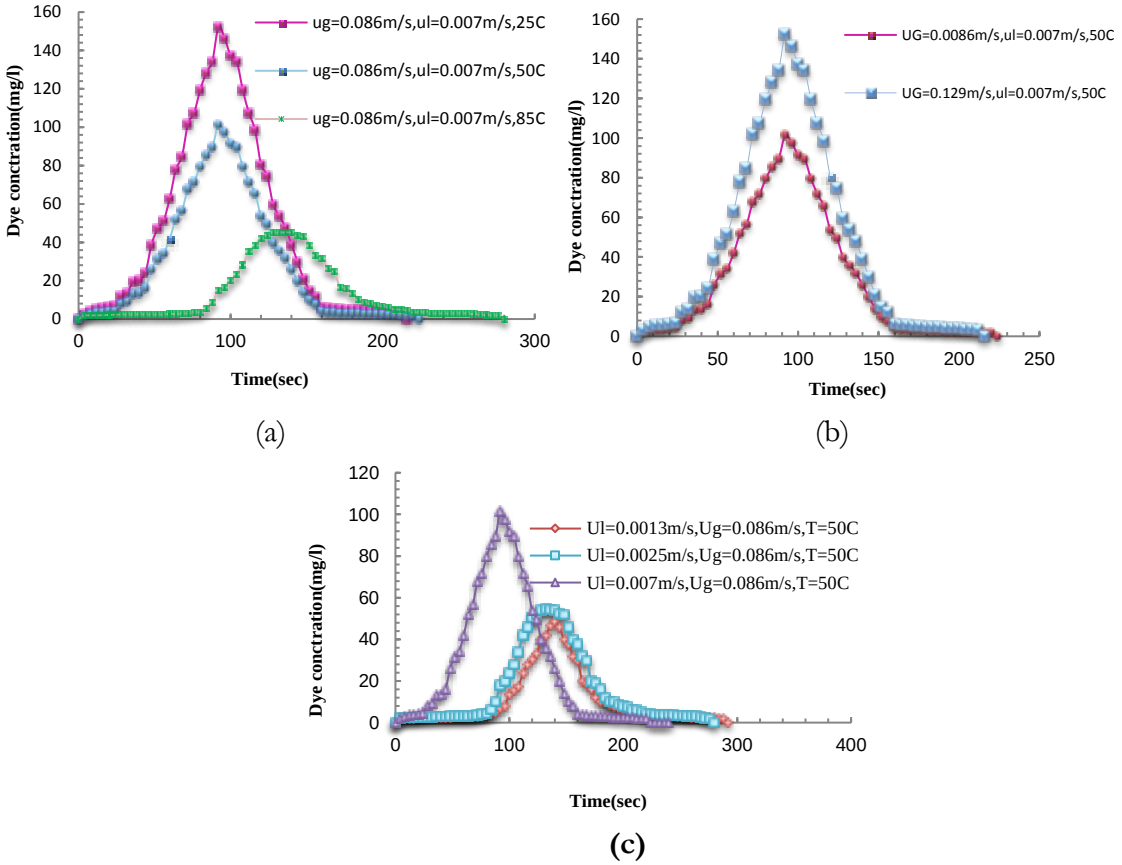


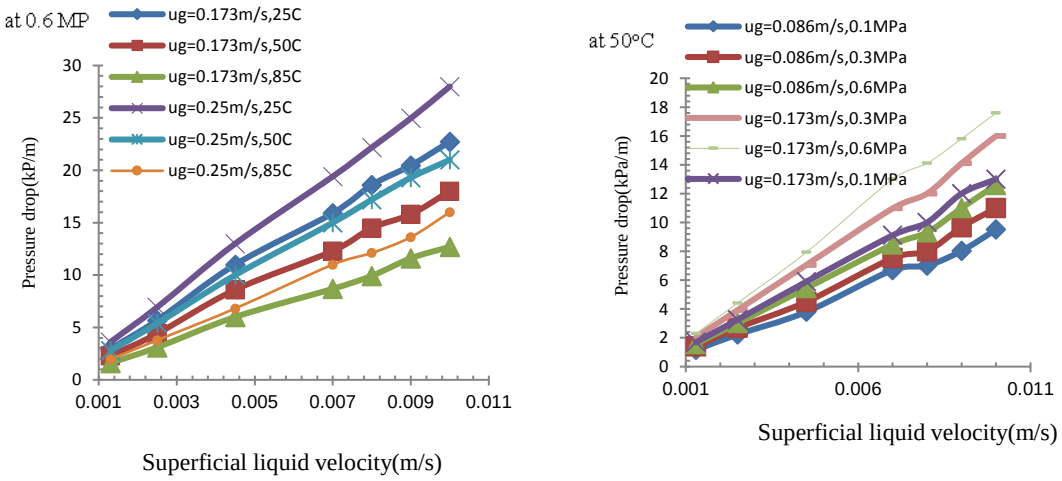
Figure (4) (Dye concentration vs. time)

Results and Discussion

Effect of operating conditions on hydrodynamic parameter -Pressure drop

Figure 5, depicts the effect of superficial gas and liquid velocities on pressure drop at a given reactor pressure and temperature. As expected, the figure shows a proportional relationship between pressure drop and superficial gas and liquid velocities. The increasing pressure drop may be attributed to the increased shear stresses exerted by the drag forces between the phases. These results are in agreement with [10,13,21-23]**.** Figure 5b show the effect of operating pressure on the pressure gradient along the trickle bed reactor. As indicated before; the pressure gradient depends, besides the bed characteristics, on the velocities of both phases and on physicochemical properties of the flowing fluids. Regarding the fluids physicochemical properties, mainly gas density is influenced by pressure. Thus for a given gas and liquid velocities, a higher gas density produces a higher interfacial drag force equivalent to a higher pressure gradient. The pressure drop is more sensitive to velocity changes than to pressure changes . This result is

attributed to the fact that in the first case, elevated pressure results in higher gas density, which consequently produces a higher drag force at the gas-liquid interphase and lower inertia force of the gas-phase. In the second case, at high superficial gas velocity, the pressure drop increases in comparison to the gravitational force which is more affected than the drag force at high pressure and low gas velocity. These results are in agreement with the finding of Guo and Al-Dahhan [14]; Urseanu et al.[7] and Al-naimi et al.[24].

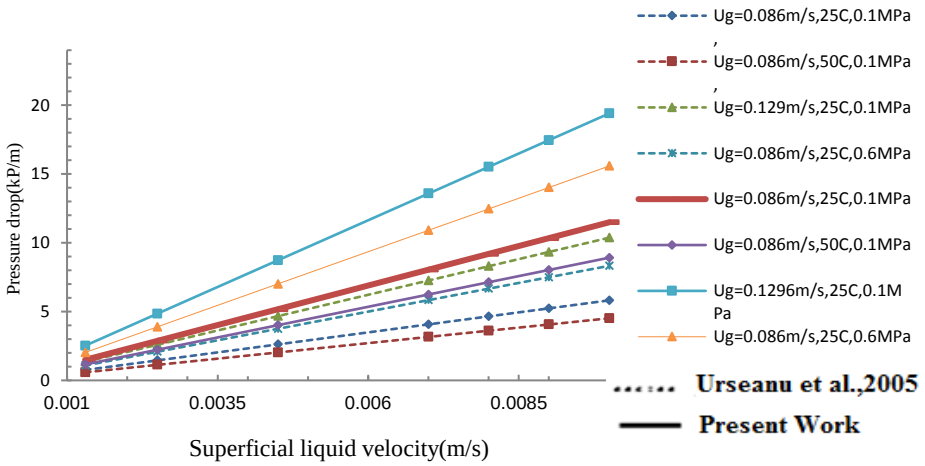


(a) **(b)**

Figure (5) Pressure drop as a function of superficial gas and liquid velocities.

Figure (5a) illustrates the effect of operating temperature on the pressure gradient along the reactor for various superficial gas and liquid velocities and pressure. Also the pressure drop decreased with increasing temperature. As indicated before, under the present conditions, pressure drop mainly depends on viscosity, density, surface tension and velocity of the fluids. As the liquid viscosity decreases with respect to temperature, the gas viscosity follows an opposite trend, the net of shear stress at the gas-liquid and liquid-solid interfaces is not obvious, since the effect of temperature on gas viscosity is less pronounced in comparison to that on liquid viscosity, increased temperatures are likely to weaken the frictional forces at the gas-liquid and liquid-solid interfaces. An additional contributing factor in favor of influence is that the pressure drop decreases with elevated temperatures due to the decrease in gas phase inertia with temperature (via gas density). These results illustrate how pressure drop behaves as a function of shear stress and inertial forces. Also at high superficial gas and liquid velocities, the effect of temperature

on pressure drop is more significant. These results are in agreement with findings of Aydin and Larachi, [25,26] and Al-naimi et al.[24]. Figure (6) shows the comparison between the present work with data of **Urseanu et al.[7]**.



Figure(6). Effect of temperature, pressure, superficial liquid and gas velocity on pressure drop in comparison with literature.

-Liquid holdup

Liquid holdup results from the balance between the driving forces and the resistances. Figure 7 shows a proportional trend between superficial liquid velocity and liquid holdup at a given superficial gas velocity. While superficial gas velocity has an adverse effect on the liquid holdup. The increase in liquid holdup with liquid throughput is due to film thickening on the catalyst particle. The reduction in liquid holdup with gas flow is attributed to the drag force at the gas-liquid interface, which is a driving force for the liquid flow (co-current flow). This drag force depends on gas velocity and density. Hence the drag force increases with gas velocity and density, shorter liquid mean residence time arise occasioning a reduction in liquid holdup. These results are in agreement with findings of Chander et al.[27] ,Guo and Al-Dahhan, [14] and Aydin,[28]. It was shown from figure(7) an adverse impact of operating temperature on liquid holdup, the liquid holdup decreases with increasing temperature at constant superficial liquid and gas velocities. This can be explained by a decrease in liquid viscosity as temperature increases, so the shear stress at the gas liquid and liquid - solid interfaces decreases resulting in lower liquid holdup. Liquid surface tension which is a resisting factor to gas flow, decreases with temperature thereby reducing the number of events corresponding to film collapse around and between particles. These results are in agreement with findings of Aydin and Larachi, [26] and Al-naimi et al., [24]. Figure (8) shows the comparison between the present work with data of Al-naimietal.,[24] .

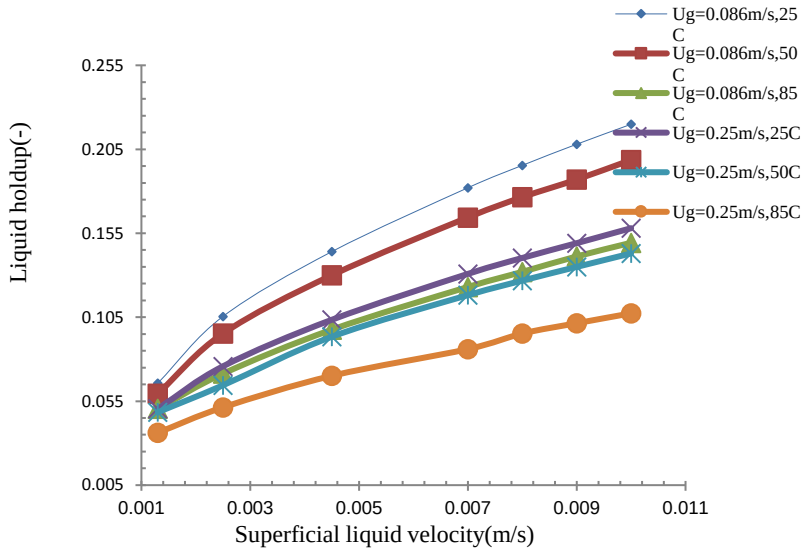


Figure (7). Liquid holdup as a function of superficial gas and liquid velocities and temperature.

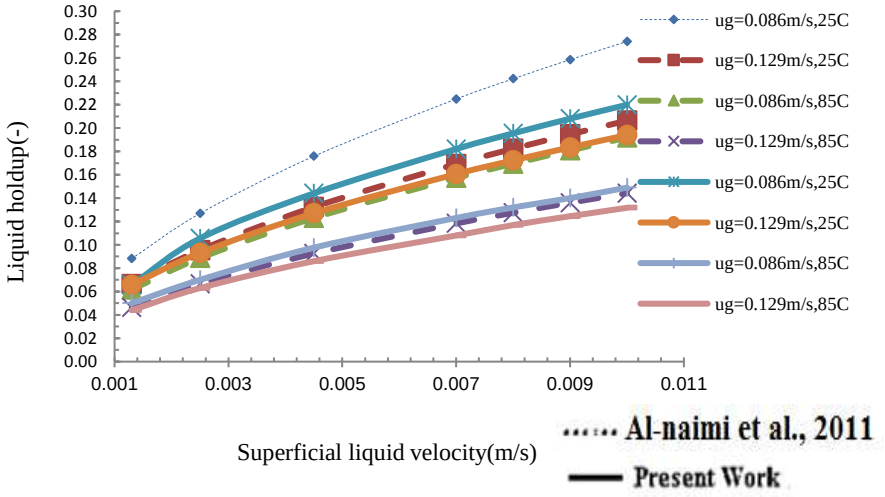


Figure (8).Effect of temperature, superficial liquid and gas velocity on liquid holdup in comparison with literature.

Axial Dispersion

Figure(9) illustrates the effect of superficial gas and liquid velocity on the liquid axial dispersion coefficient. The figure shows a positive trend between the gas and liquid velocity and the dispersion coefficient and this can be attributed to the effect of back mixing in the liquid phase. These results are in agreement with findings of Aydin, [28] and Houwelingen et al.[29].The variation of liquid axial dispersion with operating temperature is shown in Figure. As clear from this figure the dispersion coefficient decreasing with increasing temperature. This may be described by lowering in back mixing due to a decrease in liquid holdup with temperature. These results are in agreement with findings of Aydin and Larachi, [25]. Figure (10) shows the comparison between the present work with data of Aydin and Larachi, [25].

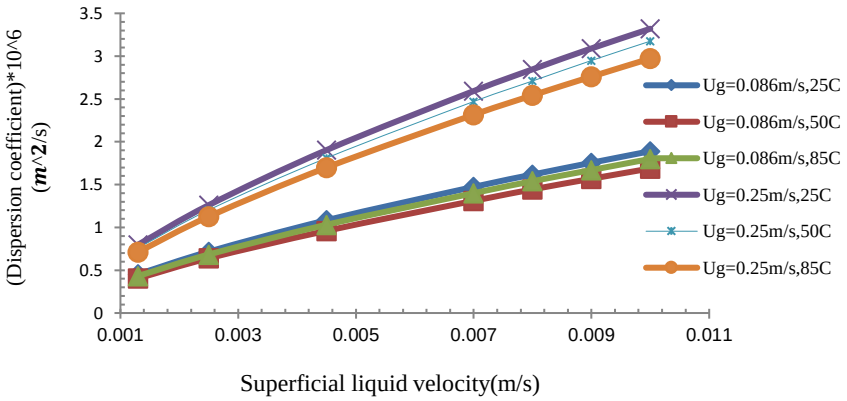


Figure (9).Dispersion coffesent at set of operating condition

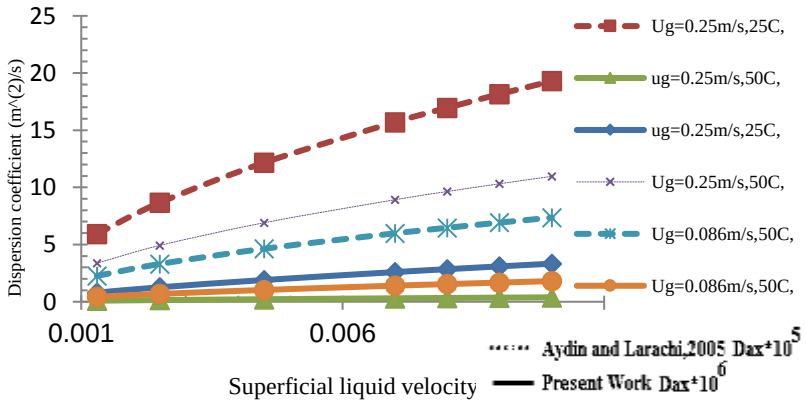


Figure (10).Effect of temperature, superficial liquid and gas velocity on Axial dispersion coefficient in comparison with literature.

Empirical Correlation

The pressure drop, dynamic liquid holdup and axial dispersion are correlated in this work where the operating parameters (superficialgas and liquid velocities)are taken into account ,the relevant system properties (viscosity,densityandsurfacetension) varied in the experiments due to variation in reactor pressure and temperature, as follows:

$$\varepsilon_L \alpha U_{L,}, \frac{1}{U_g, T} \quad \ldots\ldots 1$$

$$\Delta P \alpha U_L, U_g, P, \frac{1}{T} \quad \ldots\ldots..2 \quad ٢$$

$$D_{ax} \alpha u_L, u_g, \frac{1}{T} \quad \ldots\ldots\ldots 3 \quad 3$$

Therefore the following correlations are proposed:-

$$\frac{\Delta P}{\Delta z} = a_0 U_g{}^{b_0} U_l{}^{c_0} \varrho_G{}^{d_0} \mu_L{}^{e_0} \quad \ldots..4$$

$$\varepsilon_d = a Re_L{}^{b} R_g{}^{c} Ga_L{}^{e} \quad \ldots\ldots.5$$

$$D_{ax} = a\, Re_G{}^{b} Re_L{}^{c} Ga_L{}^{e} \quad \ldots.6$$

The pressure drop,and dynamic liquid holdupdata for air–water system was fitted to the form of
Eqs. (1),(2) and (3) by non linear least-squares regression analysis ai and exponent's bi, ci, di, ei, fi as

$$\frac{\Delta P}{Z} = 5.6836 * 10^4\, U_G{}^{0.51}\, U_L{}^{0.88}\, \varrho_G{}^{0.18}\, \mu_L{}^{0.47} \quad ٧$$

R=98.47%

$$\varepsilon_L = (3.329E+3) Re_L{}^{0.5377} R_g{}^{-0.3053} Ga_L{}^{-0.51} \qquad R=99.22\%$$

$$D_{ax} = 1.34E-5\, Re_G{}^{0.7} Re_L{}^{0.53} Ga_L{}^{-0.32} \qquad R=99.7\%$$

A experimental results and the Predicted values are shown in Figure.11 comparison

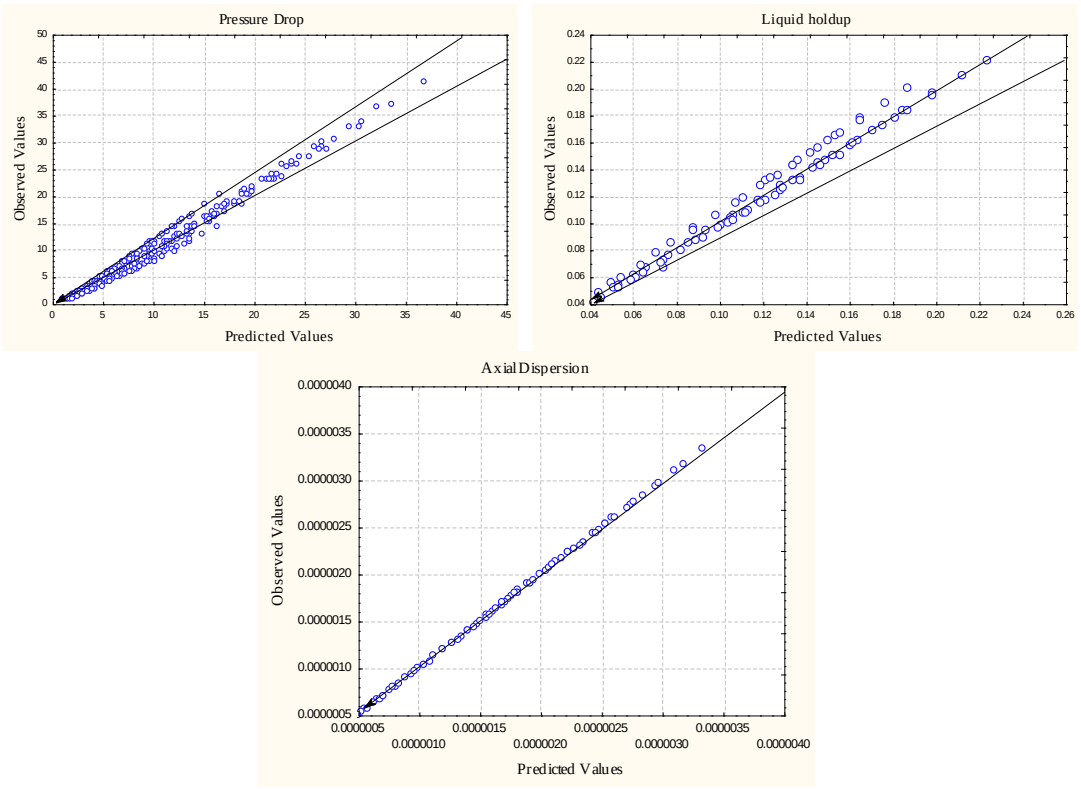


Figure (11).Observed and predicted values of empirical correlation estimated of Pressure drop, Holdup and Axial dispersion.

Conclusion Remark

1. Both gas and liquid superficial velocities have positive impact on pressure drop and axial dispersion.
2. Operating temperature has negative impact on pressure drop, liquid holdup and axial dispersion.
3. Increasing of reactor pressure caused to increase in two phase pressure drop
4. Liquid holdup was decreased by increasing gas superficial velocity while it increased with increasing liquid superficial velocity.

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