SINDH UNIVERSITY RESEARCH JOURNAL (SCIENCE SERIES)
ISSN (Print) 1813-1743, ISSN (online) 2791-0547
Vol. 54 No. 01 (2022)
https://doi.org/10.26692/surj.v54i1.4496

Efficacy of Intensified Parameters in the Trickle Bed Reactors towards an Optimum Performance

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Article history
Submitted March 2021
Reviewed Feb. 2022
Accepted March 2022

Abstract
The up-gradation in Trickle bed reactors performance obtained by varying process hydrodynamics and raw feed materials to acquire a uniform reactive region. The primary objective of this review study is to develop novel empirical approach which solely exemplifies the reaction setup and hydrodynamics for better reactor performance. The transformation of single phase into the intermediate phase and then to product is quite dependent on raw material characteristics and reactor's geometrical features. The main streams in these reactors are fed at high pressure. The flow region in Trickle bed reactor depends upon pressure drop, fixed bed temperature and hydrodynamics of the liquid phases. The experiments on reaction rate are concerned with mass transfer diffusion between the reactive phases. It is observed that diffusion rate is decreased by increasing the liquid recycling. Hence, the reaction rate becomes lower and it effects the overall yield of the Trickle bed reactor. In conclusion, this review study gives the understanding of the hydrodynamics and its dependencies on various factors such as particles void fraction, product yield, reactive flow region and liquid phase velocity. It results in a novel solution which elaborates the complex reaction and phase dynamics. The shock waves recorded from the Trickle bed reactor column confirm reaction on catalyst bed. The Trickle bed reactor is helpful in dealing the processes with high pressure and temperature. This work forecasts better process selectivity for this model which makes it commercially successful.

Keywords: Hydrodynamics, reactions, liquid and gas phases, process intensification

Introduction

The Trickle bed reactors are used commercially in different chemicals production applications. These reactors have a vital role in petrochemical plants for desulfurization of process materials, oily products and oxidation reactions. There is a non-uniform temperature distribution in Trickle bed reactors due to the formation of hot spot on reaction phase. These reactors also have an application in biochemical industry [1][2][3][4]. It is called three phase reactor (Feed is liquid and gas phase, catalytic bed is solid). The fixed bed of catalyst upgrades the process yield effectively [5][6]. There is also employed an approach for regeneration of catalyst bed due to choking on its surface during the process. The typical trickle bed reactors are used for high flow of feed as liquid and gas phases. The conventional operation of Trickle bed reactor is at adiabatic state with high temperature and pressure values [7][8][9].

The reaction kinetics and thermodynamic studies on the Trickle bed reactor are done on high temperature and reactant gas flow. The reactant gas must have the sufficient contact time with liquid phase for better mass transfer diffusion. This approach is developed for establishing an empirical model to obtain high yield and selectivity of the process. Feed at different pressure ranges is fed in Trickle bed reactor for improving the gas solubility in liquid phase by attaining larger mass transfer co-efficient [10][11][12][13][14].

Cite this:
Suri SK. M. Siddique, SA Soomro, and S. Aziz (2022). Efficacy of intensified parameters in the Trickle bed reactors towards an optimum perforamance. Sindh Uni. Res.J. (SS) 54:1. 51-59

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Recently, many researchers focused to develop an empirical approach to up-grade the Trickle bed reactor performance via liquid hold-up time and its flow rate. For this purpose, the liquid showered on the catalyst bed with gas phase comes at uniform rate from bottom. The liquid phase plays an important role for the reactive flow region. It is observed that liquid phase provides resistance for gaseous phase which may results in a relatively lower performance for Trickle bed reactor [15][6].

The reactive region of the Trickle bed reactor is critical for the reactants. The feed flow rates are derived for equal liquid distribution throughout the solid bed. The Trickle bed reactor performance is related to pressure drop, liquid holdup and interphase mass transfer diffusion. The elimination of the hot spot in the reactive flow region is necessary to avail high selectivity. The biological reaction in Trickle bed reactor incorporates the immobilized cells. The liquid phase overlaps the particles and molecular diffusion takes place. Extraordinary results can be achieved by focusing on an optimum feed flow rate [16][17][17][18][19][20][21].

The primary objective of this review work is to up-grade the Trickle bed reactor performance with the novel and optimized operating parameters keeping in view the reaction hydrodynamics and reactant flow rates. This parametric study is highlighted in literature review section. This review study is based on the novel understanding of reactor process intensification which is essential to be focused by the scientists working in this field. The experimental results proved that these novel parameters are vital to up-grade the reactor performance. The discussed results in the corresponding review section of this study enable us to improve the chemical process intensification for the Trickle bed reactors. Therefore, developing a better understanding of the Trickle bed reactor novel intrinsic parameters leads to an efficient reactor. The better reactor efficiency is of great importance in the current energy resource scenario of the world.

Trickle bed reactor design with the hydrodynamics parametric study

Naimi, Jasim, Sudani and Essam did the research work on hydrodynamics and changes in flow region at different temperature and pressure ranges in the Trickle bed reactor. In this study, the hydrodynamics are analyzeded for (Air-Water-Acetone) mixture in the reactor system shown in figure 1. The reactor system and catalyst properties are illustrated in Table 1. The main Trickle bed reactor setup to study the reactant fluid hydrodynamics is comprised of stainless-steel vessel with 1.25 m length and 0.05 m dia. Different packings of the catalysts bed in the reactor are installed for acquiring optimum performance. The reactor top has a pre-packing layer with inert particles to achieve equal distribution of reactive phases throughout the bed. The optimum catalyst (0.5% Pt/Al2O3) bed height is about 90 cm. The optimum particle diameter to reactor diameter ratio is 0.2 m which supports the optimum performance for high selectivity [22].

There are mainly sixteen operating features of the reactor parameters which are; (i-Number of tests runs for high efficiency (N), ii- Trickle bed reactor total Pressure through reactor height (P), iii- liquid hold-up or closure (εL), iv- Reynolds number of liquid and gas phases (Re), v- Gas hold-up (εG), vi-Pressure drop through catalyst bed, vii- Total pressure drop in reactor, viii- Conductance of catalyst bed (C), ix- Equivalent particle diameter of solid phase (De), x- Particle diameter of solid phase (Dp), xi- Gravitational acceleration liquid and gas phases (g), xii- Reactor height (Z), xiii- Liquid phase flow rate (L), xiv- Gas phase flow rate (G), xv- Dynamic viscosity of liquid and gas phases (μ) and xvi- Density of three phases (liquid, gas and solid); (ρ)).

Hydrodynamics process intensification parameters

It is hard to understand the fluid hydrodynamics stated above. In the process industry, optimum pressure and temperature ranges play a crucial role for obtaining high process efficiency. Therefore, there is a need to optimize the process with reliable features which help in producing high yield. Thus, reactive flow region is related to transition flow region.

It is quite simple to explain process hydrodynamics such as (Bed voidage (ε), Liquid hold-up (εL) and Gas hold-up (εG)) through an experiment by using an

Table 1. **Trickle bed reactor and catalyst properties [23][24][25][21][26].**

Sr. No.	Properties	Specification
1	Trickle bed reactor inside diameter (I.D)	5 cm
2	Trickle bed reactor height	125 cm
3	Catalyst material	Aluminia joint with 0.45% pt
4	Catalyst porosity	0.37-0.39
5	Catalyst bed temperature	29-139 °C
6	Gas phase velocity	7-25cm/s
7	Liquid phase velocity	0.29-2.4 cm/s
8	Pressure	0.2-1.1 MN/m^2
9	Catalyst bed area	300000 cm^2/s

organic liquid with low surface tension. The organic liquids are useful industrial chemicals.

Hydrodynamics parameters

The results for the pressure drop through the bed of inert glass material are analyzed. Glass material shape is recorded by using transducer.

A Non-continuous flow region appears between the reactive and pulsed flow regions due to reactants velocities (Gas and Liquid). The catalyst bed temperature and its total pressure have an increasing linear relationship with the liquid and gas phase velocity.

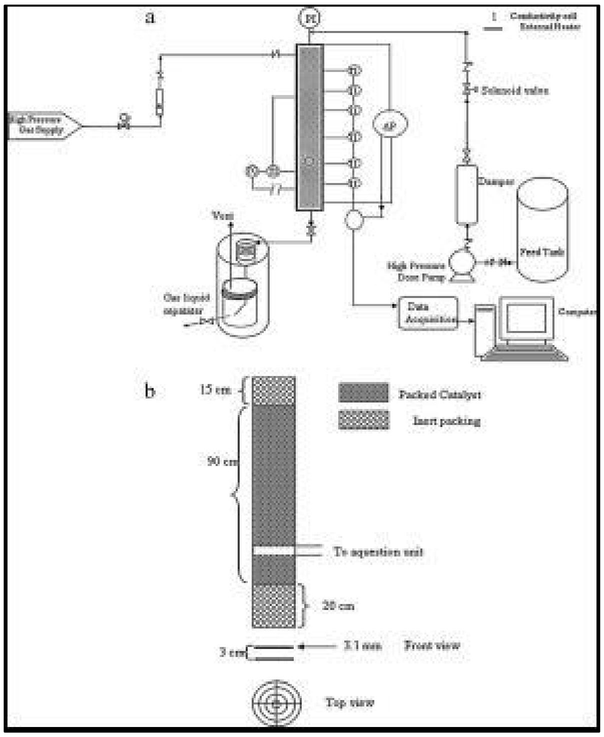

Figure.1. (A) Demonstration of Trickle bed reactor setup for derive hydrodynamics study. (B) Demonstration on Trickle bed reactor catalyst bed layout [22].

The different phase interaction in trickle bed reactor effects reactive flow region which depends on feed rate and thermochemical properties of fluid. In an effort to distinguish trickle phase and naturally occurring pulse flow regions, an approach is established to combine the gas and liquid feed arrangement by using different temperature and pressure values.

Effect of Pressure Variation and Liquid Closure

It is observed that superficial gas velocity in catalyst bed causes increase in gas and liquid velocities which produce high pressure drop for (Air-Water-Acetone) system. It is proved that an increase in pressure drop tends to enhance molecular diffusion between the

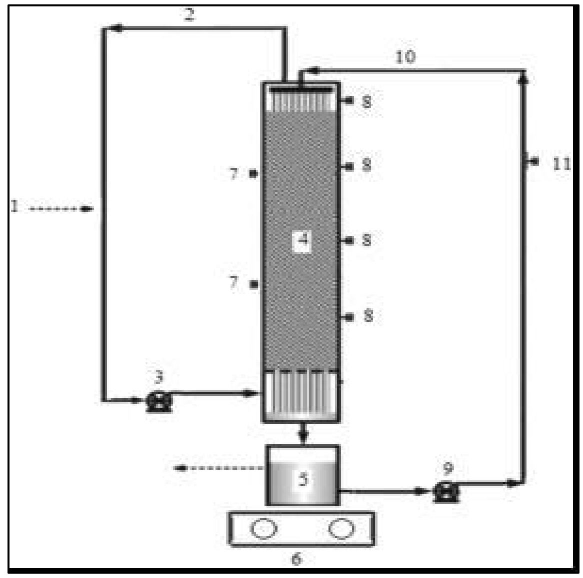

Figure.2. Demonstration of Schematic diagram of trickle bed reactor system [27].
(1) Air feed-inlet (2) Air recycling (3) Air recycling pump (4) Trickle bed reactor (5) Vessel with product (6) Magnetic heating stirrer (7) Bed ports (8) Air ports (9) Feed pump (10) Recycled liquid (11) Recycled liquid ports.

liquid-gas interfaces in the reactive region. Thus, molecular diffusion increases the reaction rate of (Air-Water-Acetone) system.

Bio-Chemical Process Intensification

Seghidi, Zamir, and Vahabzadeh did the research work on cometabolic degradation of ethyl mercaptan with phenol. They utilized Ralstonia eutropha in suspended growth and gas-recycling Trickle bed reactor system is shown in figure 2 [27].

In their work, the biodegradation process of Ethyl Mercaptan with phenol in suspended growth and gas-recycling intensified by using Trickle bed reactor. The main chemicals used to intensify the solid growth media process are: (Glucose-3, Yeast extract-2, Pepton-2, Mono-potassium phosphate, Amonium Sulfate, Magnesium Sulphate and Agar). The pH of the solution maintained around neutral value of 7, using NaOH solution.

Bio-Chemical Process Intensification Study

The biochemical degradation of Ethyl Merceptans from phenol mobilized cells, is intensified through series of experiments by operating lined Trickle bed reactor with arrangements of figure 2.

Result: The biochemical reactions result shows that Ethyl Merceptans recovery is optimized at low feed concentrations. This bio-chemical reaction could not be achieved to the maximum yield at high feed concentration of Ethyl Merceptans [28].

Reactions Kinetics Study In Trickle Bed Reactor

Maleki, Motamedi, Sedighi, Zamir, and Vahabzadeh did the investigation via experimental and kinetics

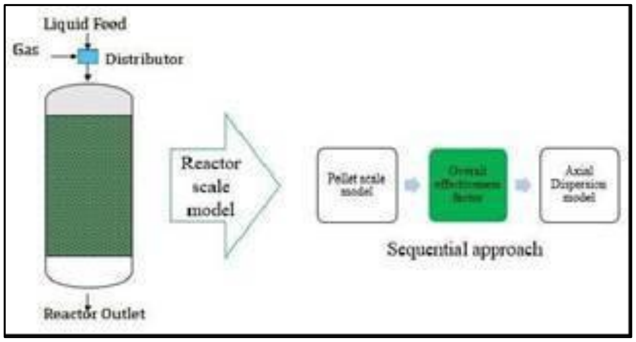

Figure.3. Demonstration of Trickle bed reactor pellet scale and axial dispersion models [37].

modeling study for cometabolic degradation of p-nitro-phenol. They used loofa- immobilized Ralstonia eutropha. In their work, the main objective was to examine the reaction kinetics of bio-chemical degradation of Ethyl Merceptans [29].

The reaction rate is affected by parameters such as bed voidage; which is higher than the bed wall. The cells accumulate on the bed surface and form a matrix. Therefore, reaction rate is dependent on initial Ethyl Merceptan and biomass concentrations. The Monod kinetic model incorporated for the Ethyl Merceptans and phenol with the experiment tests. The biodegradation of bacteria is carried out by using phenol as a carrier.

This experimental research study on the Trickle bed reactor is done through the immobilized cell with Kissiris catalyst bed using Ralstonia eutropha as a micro-organism. The degradation of p-nitrophenol ranging from 5 to 15 (mg/L) was degraded almost completely by free cells of R. eutropha. Ethyl Merceptan concentration from 10.1-14.4 (mg/L) in an aqueous phenol solution is observed with removal efficiency from 72-98 %. The observed results demonstrate the Ethyl Merceptan degradation from the bacterial cells with phenol as carrier and Ralstonia eutropha as surfactants [30][31][20][32][27][33][34].

Trickle Bed Reactor for Simulation of Reverse Osmosis Process for Water Purification

Obaidi and Jaraullah did the research work with computational fluid dynamics codes for the simulation of reverse osmosis process in Trickle bed reactor. Phenol and its derivatives compounds are extremely toxic in nature and create disagreeable effects on living beings. Till the recent past, the Trickle bed reactor setup is used for the removal of phenol from industrial waste water. In this study, an integrated reverse osmosis process in Trickle bed reactor is developed for phenol removal from waste water. This integrated model is able to remove high concentration of phenol. This process simulation model is validated with experimental data by coupling the hybrid process [35].

Hybrid Trickle Bed Reactor for Reverse Osmosis Process:

The most used process for the removal of toxic contents from waste water is catalytic wet air oxidation process. In reverse osmosis process oxidation of organic matter takes place at operating condition (100–350 °C, 4.93- 197.38 atm). While, the reverse osmosis process is being used for the removal of low content of organic matter from waste water. These two discussed processes are combined to provide a hybrid model. It is comprised of a fixed bed of catalyst material from where waste water feed is

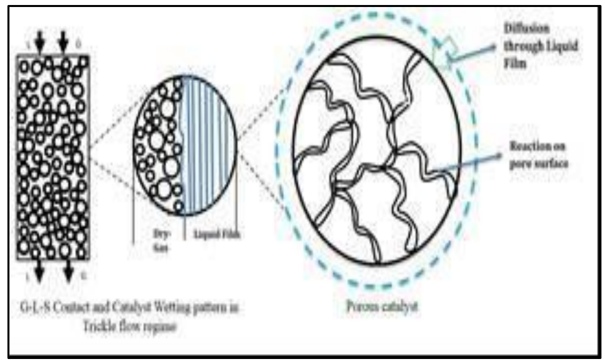

Figure.4. Demonstration of catalyst wetting action in the Trickle flow region [37].

pumped under variable operating conditions such as initial phenol concentrations, oxygen partial pressure, reaction temperature, and liquid hourly space velocity and gas flow rate.

Modeling of Hybrid Trickle bed reactor for Reverse Osmosis (RO) Process optimization:

There is a requirement of modeling a process to obtain the optimum process conditions for different process designs. In this work, the Langmuir-Hinshelwood model is used to optimize the Trickle bed reactor for an upgraded performance. The Trickle bed reactor is used for the oxidation of phenol from industrial waste (waste water) by using oxygen and catalyst (Pt/ɣ–Al2O3). This proposed simulation study is comprised of different differential and algebraic correlations which coincide heat and mass balances with their physical properties.

Phenol removal from 95.384–99.145% in industrial waste water is achieved. This integrated Trickle bed reactor's simulated process model is able to increase the removal of phenol from 4– 55% efficiently [36].

Catalyst Effectiveness for Upgradation in Trickle Bed Reactor Performance

Shariff and Dhhan research work comprised on the simulation of Trickle bed reactor. The selected process is the hydrogenation of Alpha-methyl-styrene (AMS) with a specific liquid phase residence time. It is carried out with a steady state diffusion model which shows the effectiveness of catalyst factor for upgradation in Trickle bed reactor performance. The total catalyst effectiveness is taken from various reactor scale models. This simulation assessed the experimental tests by evaluating the catalyst effectiveness from pellet scale model and axial dispersion model shown in figure 3. The conclusion is that the reactor performance is in agreement with the experimental results from the models of pellet scale and axial dispersion. It coincides to the fitted polynomial of the reactant concentrations and catalyst effectiveness factor that increase the selectivity of this Trickle bed reactor [37].

There are different performance factors to examine the Trickle bed reactor such as incomplete catalyst wetting, interphase mass transfer and diffusion. There comes unsteady irrigation with low liquid phase flow which causes partial wetting of the catalyst and high maldistribution in Trickle bed reactor. It leads to three phases (liquid, solid and gas) reactions. Henceforth it is crucial to examine the physical factors for the upgradation of a reactor process selectivity. It is also necessary to interpolate the diffusion of the reactant phase in the pores of the catalyst pellets. There is may face a resistance at inter-particle diffusion in reactants with porous catalyst described in figure 4. In this regard, the heterogeneous models are practiced which have high accuracy as compared to homo and pseudo-homogeneous models.

It is necessary to find the effectiveness factor of the catalyst to overcome any flaw in the design of the reactor. Furthermore, there is increase in the axial dispersion by the time. The (Pellet scale modeling (PSM), Sequential approach model (SQM), Fitted Polynomial model (PNM), One effectiveness factor model (OEM) and Axial dispersion model (ADM) are used. The maximum yield of Alpha-methyl-styrene (AMS) is up-to 80%. This finding proves the operability of Trickle bed reactor with combination of PFM and SQM models. There is achieved 70 % yield of the Alpha-methyl-styrene (AMS) process by using the combination of (ADM) and (OEM) models and 60 % yield of the Alpha-methyl-styrene (AMS) is obtained by combining (PFM) and (SQM). Hence, it has been proven that the utility of catalyst can increase the process yield and its relative selectivity significantly by using the mathematical correlations demonstrated in figure 5.

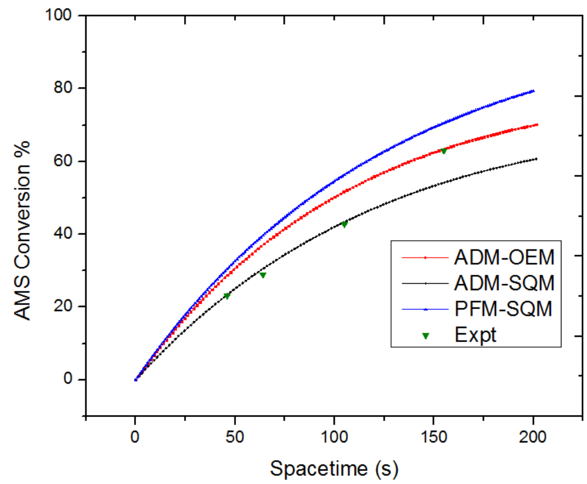

Figure.5. Demonstration of Alpha-methyl-styrene (AMS) process yield for upgradation in Trickle bed reactor process intensification using combinations of different mathematical correlations [37].

These mathematical models are useful for this estimated performance of a reactor by evaluating the optimum condition for catalyst effectiveness. Furthermore, It is helpful to decrease the errors occurred in reactor design and scale up [38].

Simulation for on Liquid Volume Fraction for Upgradation in Trickle Bed Reactor Performance

Dharnaj and Buwa did the research work to increase the effectiveness of performance parameters of Trickle bed reactor by evaluating liquid volume fraction. In their work, computational fluid dynamic tool Eulerian-Eulerian model was used for local liquid distribution in Trickle bed reactor. The modeling was carried out with pseudo-3D Trickle bed reactor column. The liquid and gas phases were fed from the reactor top and there is pressure outlet at the bottom as shown in figure 6. The capillary pressure force Fc investigated and found that it is related to capillary pressure Pc. The modified FC showed the time averaged local distribution eL at various values of liquid phase flow and its distributor configurations [39][40].

The dynamics of local liquid distribution is measured by using capillary pressure force model FC. It is found that to investigate the time-averaged spatial (eL) distribution is good. It elaborates the liquid distribution as a function of time. It is quite helpful to predict the liquid phase velocity. The liquid is pulsated for a period of 10 s and its volumetric flow rate changes during this. The total volume of the liquid pulsated in this experiment is (861-979 ml). From this data average volume is estimated. The evaluation of time eL with the diameter of the trickle bed reactor column at h=0.174 m is demonstrated in figure 7.

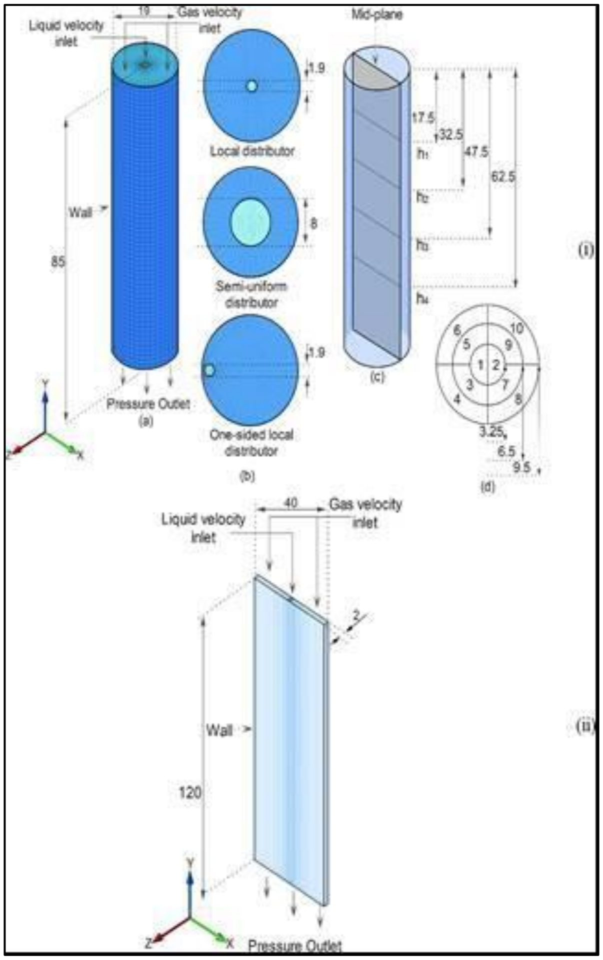

Figure.6. Demonstration of Trickle bed reactor computational configuration (i) (a) mesh and physical conditions, (b) distributors considered, (c) mid-plane, lines considered for analysis and (d) liquid collector configuration for cylindrical column and (ii) for rectangular column [39].

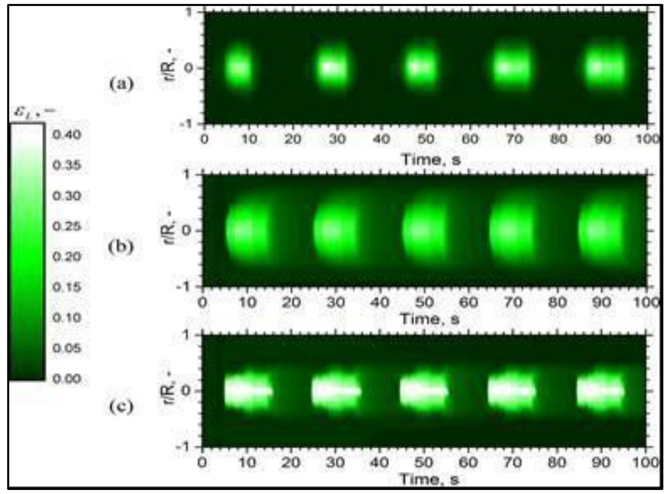

Figure.7. Demonstration of time-evolution of measured and predicted radial eL distribution for synthetically created pulsing flow at h = 0.175 m. (a) (ERT) measurement of and predictions using (b) empirically corrected capillary pressure model of Attou and Ferschneider, and (c) FC = 0 [39].

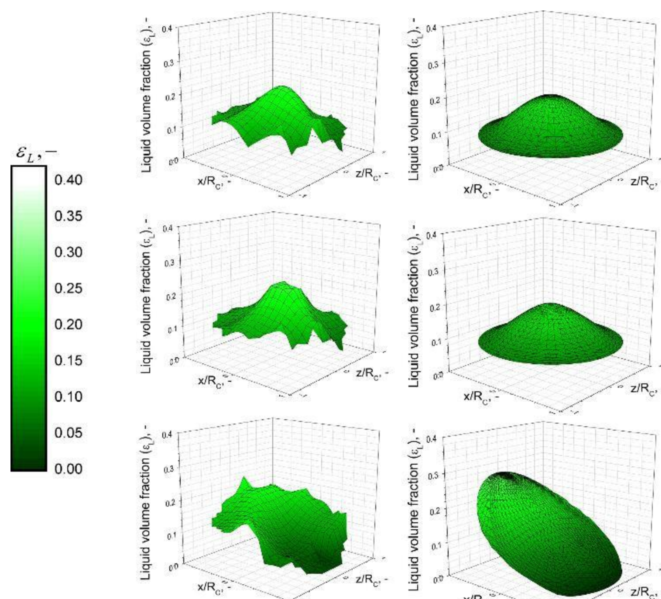

Figure.8. Demonstration of liquid distributor configuration effect on measured and predicted eL distribution over r-h plane at h = 0.175 m for (a) local distributor (b) semi-uniform distributor and (c) one-sided local distributor [39].

Simulation model shows different positions of the liquid pulses as the function of time. In Figure, liquid distribution precisely elaborated at d=0.7m. On the other hand, the Electric Resistance Tomography (ERT) measurement does not predict the transient variation of liquid phase. It is inferred that (ERT) can measure the liquid phase distribution at low concentration if the liquid phase is in steady state condition. In steady state condition, the residual liquid is high and the new stream of liquid in pores is in transition condition. There are colored images of liquid flow patterns on the bed and the path on which liquid gets saturated. There are executed different numerical modeling by keeping FC to zero. There is an observation that liquid spreading gets minimized, shown in figure 7 (c).

The figure 8 shows the measured and predicted liquid distribution eL on r-h plane at h = 0.625 m. It is clear that FC demonstrates the liquid distribution by using various distributors configuration. Moreover, the one-sided distributor does not elaborate the quantitative radial liquid spreading effectively. No improvement observed in model prediction when the mathematical modeling performed with high liquid flow on the wall. It is due to the fluctuation in radial porosity while liquid distribution is constant.

Conclusions

1. To study the hydrodynamics parameters of a chemical reactor are quite complex for a real understanding of the processes. The current findings reveal that effect of particle void fraction becomes rather complicated to be analysed for the product yield attained by the reactor. Moreover, due to the reactive phase molecular diffusion, an intermediate reactive region is dependent upon the particle void fraction. Also, there appears a bubble phase which is transitory in nature. The experimental tests focused on the relative pressure and velocity conditions of the reactive region clearly indicate that the liquid phase velocity is solely dependent on gas phase superficial velocity. The empirical approach is being developed to examine the transition of reactive flow region to bubble phase. A large network of databases including process selectivity, feed and product nature is essential for above cited literature to gain a commercial success.

2. The present research review data is quite helpful to simulate the Trickle bed reactor. A deep understanding is being developed by using the non-Newtonian fluids which are the focus of many researchers in the advanced research sectors. The most authentic experimental research study on a Trickle bed reactor carried out with feed flow rates and reactive phase concentrations by using non- Newtonian fluid system.

3. The use of surfactant or depressant has a significant role in industrial chemical production. There are observed a fluctuation in pressure drop of trickle bed reactor due to given feed flow rates. The reactive flow region transfers the superficial gas phase velocity to the liquid phase solution. There is high pressure drop with the increase in gas velocity. There is an observation from many researchers who worked on trickle bed reactor dynamics that an increased pressure fluctuation is observed due to (Foaming on bed, Breakage and Reformation) in the reactive flow region.

4. Computational fluid dynamics tools have some real potential to simplify complex process dynamics like in trickle bed reactor. The computational fluid dynamics play a key role to integrate experimental studies into a unified framework. The formulation of multiphase reaction kinetics and hydrodynamic models results in a reliable and efficient technology for waste water treatment, using trickle bed reactor. It leads to a novel modelling solution for a relatively complex reaction and phase dynamics.

5. Shock waves observed from a Trickle bed reactor column, when there is a step change in liquid feed. These waves shift towards the catalyst bed with larger velocity than the liquid phase. It clarifies that the reaction on catalyst bed with fresh or regenerated surface separates undesired products. The shock waves are measured by feed liquid and the liquid hold-up using Wallis equation (derived in 1969).

6. In my current review, I studied the essential parameters like particle diameter, particle shape, bed voidage, liquid and gas phases velocities, surface tensions and intermediate phase (Reactive phase) till the last stage to get the final product (Chemical formulation). This clearly designates the broad range of Trickle bed reactor's intrinsic experimental conditions. These developed models for the Trickle bed reactor parameters which discussed earlier do not measure the reaction rate with precision. This happens due to phase transition from the trickle-pulsed phase to trickle-bubbled phase.

7. It is concluded that Trickle bed reactors are quite helpful in dealing the processes which require high values of pressure and temperature. However, the only drawback occurs for Trickle bed reactor at low feed flow rates. It is proved that outstanding starting point is quite necessary for observing real behaviour of the system. The future experimental and simulation studies on Trickle bed reactor must be based on gas phase hold-up and gravimetric techniques in the reactive flow regions.

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