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Reproducible Technique for Packing Laboratory-Scale Trickle-Bed Reactors with a Mixture of Catalyst and Fines

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A reproducible procedure for packing small-diameter packed beds with a mixture of fines and catalyst is reported. Such beds are essential for process catalyst testing in trickle-flow reactors. Packing uniformity along the bed, reproducibility of single-phase pressure drop and reproducibility of liquid holdup and two-phase flow pressure drop in repacked beds has been demonstrated.

Introduction

Trickle-bed reactors are fixed beds of catalyst contacted by cocurrent downflow of gas and liquid. They are widely used in petroleum, petrochemical, and chemical industries, pollution abatement, and biochemical and electrochemical processing. These reactors are usually employed for heterogeneous gas–liquid reactions catalyzed by the solid and for solid-catalyzed gas reactions in an inert liquid phase. The design of industrial trickle-bed reactors, needed for the development and commercialization of novel processes and products, is based on translation of laboratory (bench-scale) data to large scale (i.e., scale-up). In other circumstances, when the commercial process is well established and a commercial trickle bed reactor is in operation, laboratory studies are aimed to provide information concerning the behavior of a new catalyst, an alternative feedstock, etc. (i.e., scale-down). Both, for scale-up and scale-down applications, investigations in laboratory reactors are necessary. Current economic considerations require that the smallest possible laboratory units be used for scale-down and scale-up (Sie, 1991). This poses a number of challenges. Since laboratory scale reactors need to match the space velocity of commercial units, the actual velocities in them are much lower which may lead to incomplete catalyst utilization due to partial catalyst wetting. Moreover, the same catalyst sizes, types, and shapes employed in the commercial reactors are used in the small diameter laboratory units where the criterion of $d_r/d_p \geq 20$, desirable for avoiding wall effects, usually cannot be met. Such conditions can cause liquid maldistribution and insufficient use of the catalyst bed by reducing liquid–solid contacting efficiency (Sie, 1991; Van Klinken and Van Dongen, 1980; Duduković and Mills, 1986; Gierman, 1988).

As a remedy to the above problems dilution of the laboratory beds with fines (small, inert, and nonporous particles of about 0.1 catalyst diameter), as shown in Figure 1, has been recommended and has been utilized for decades to overcome the shortcomings of laboratory scale reactors and/or to provide better temperature uniformity in the reactor particularly for highly exothermic reactions. In this technique, fines are dispersed among the catalyst particles providing more solid–solid contact points and areas over which liquid flows, and hence fines help reduce the voidage in the bed particularly near the reactor wall. Thus, the hydrodynamics is largely dictated by the packing of the fines, whereas the catalytic phenomena are governed by the catalyst particle of the same shape, size, and form as used in industrial practice. This decoupling of hydrodynamics and kinetics is used to approach the large-scale perfor-

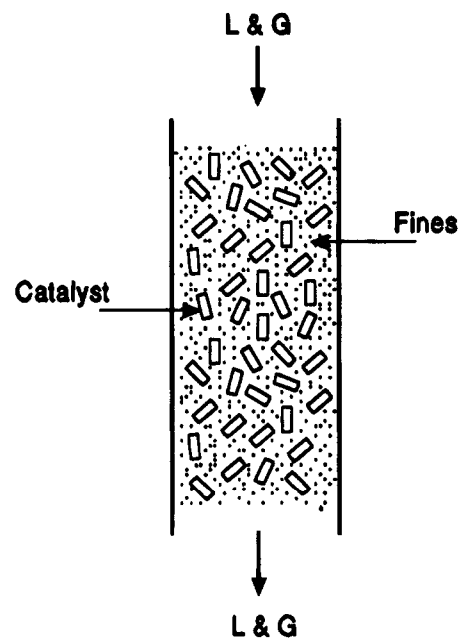


Figure 1. Schematic diagram of diluted bed with fines.

mance by improving the plug-flow characteristics of the laboratory reactor (Sie, 1991; Van Klinken and Van Dongen, 1980). This results in better catalyst utilization in a diluted bed with fines due to liquid distribution improvement (increasing liquid holdup as well), reduced wall effects, and by minimizing axial dispersion, as found by many investigators (Sie, 1991; Sedriks and Kenney, 1973; Koros, 1976; Van Klinken and Van Dongen, 1980; Carruthers and DiCamillo, 1988). Recently, Al-Dahhan and Duduković (1993) and Al-Dahhan (1993) measured at high-pressure operation liquid–solid contacting efficiency via tracer method simultaneously with pressure drop and liquid holdup in diluted beds with fines. They found that the catalyst wetting efficiency is improved in a diluted bed with fines and is strongly related to both pressure drop and liquid holdup. On the basis of their findings, at constant pressure and at fixed liquid and gas superficial velocities, larger pressure drop and liquid holdup are obtained in a diluted bed compared to an undiluted bed. As reactor pressure and gas superficial velocity increase at fixed liquid mass velocity, pressure drop increases and liquid holdup decreases, both of which cause better spreading of the liquid film over the external surface of catalyst, making the particles more externally wet.

Accordingly, the catalyst bed dilution technique has found rather widespread applications as a means for scale-up and scale-down and in testing of commercially

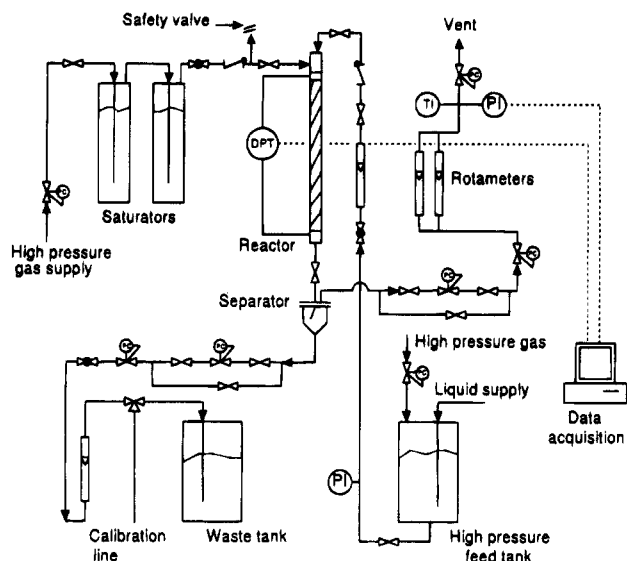


Figure 2. Process and instrumentation diagram (P&ID) of the trickle-bed reactor facility.

used catalyst particle sizes in small-scale laboratory reactors. It is noteworthy that the meaningful results of the dilution techniques would be negated if the packing method of mixing the bed of catalyst and fines fails to produce reproducible results. The studies in the open literature that utilized fines did not report how the diluted bed was packed to ensure reproducibility. However, few investigators reported only the amount of fines and catalyst used, which ranges from using just enough fines to fill the voidage of the original catalyst bed (Koros, 1976; Carruthers and DiCamillo, 1988) to 1–10 volumes of fines to 1 volume of catalyst (Koros, 1976; Gierman, 1988; Carruthers and DiCamillo, 1988; Van Klinken and Van Dongen; 1980).

In the absence of a systematic reported method of packing the small-diameter tubes with a mixture of large catalyst particles and inert fines, we embark here on a such seemingly mundane but quite important task for industrial practice. We report here our trials which have resulted in a reproducible procedure to pack small laboratory trickle-bed reactors with a mixture of catalyst and fines. Sectional testing, pressure drop, and liquid holdup measurements have all been used to quantify the reproducibility.

Experimental Setup

High-pressure trickle-bed facility has been designed and developed to operate at a pressure up to 7 MPa (~1000 psig, Al-Dahhan, 1993). Figure 2 shows the process and instrumentation diagram of the facility. The facility consists of a trickle-bed reactor setup, liquid and gas delivery systems, and data acquisition system. This facility allows low- and high-pressure experiments and measurements of liquid holdup and pressure drop simultaneously over a broad range of operating conditions. Trickle-bed reactor setups consist of different sizes of optically clear acrylic and stainless steel reactors. The reactor's gas/liquid distributor has been designed similar to the industrial type distributor to ensure uniform liquid and gas distribution at the bed inlet. The bottom of the reactor is connected to the gas/liquid separator. The separator is constructed from a thick optically clear acrylic to monitor the liquid level. A demister of stainless steel mesh is mounted in the upper part of the separator to trap the liquid mist from the gas effluent stream. Liquid phase is delivered to

the reactor by a high pressure feed tank. The exit liquid stream from the gas/liquid separator flows through back pressure regulators to the rotameter and then to the waste tank. The gas phase is delivered to the reactor from high-pressure gas cylinders. The gas is allowed to pass through two high-pressure saturators (bubblers) to be saturated with liquid in order to prevent evaporation in the reactor liquid bed. The gas outlet stream from the gas/liquid separator passes through two back pressure regulators. Upon leaving the regulators, the gas flows to high- and low-range rotameters and then to the vent. Two high-pressure differential pressure transducers (0–12.4 and 0–186 kPa), which are used to measure the pressure drop across the catalyst bed, are connected to the top and bottom of the reactor bed. Liquid holdup is measured by the draining method in which, by simultaneously shutting off the inlet and outlet streams and draining the reactor, draining holdup can be measured. The remaining holdup in the bed is measured by weighing the reactor after being drained and subtracting the weight of the dry reactor. This holdup consists of external to the catalyst and capillary (inside the pore) holdups.

The facility is connected to a portable, flexible, and user-friendly data acquisition and computation system. Detailed discussion about the design and the facility development can be found in Al-Dahhan (1993).

Developed Packing Techniques

The essential requirement of any packing technique is to ensure reproducibility of the packing. This is because even if a uniform liquid distribution is achieved at the distributor, significant bypassing (channeling) and/or segregation could occur due to the improper way the catalyst and fines are packed (Gierman, 1988). Ensuring a uniform catalyst/fines distribution along the bed and reproducing such uniformity are essential to avoid channeling and segregation. In this work different packing methods for both dry and wet packing have been utilized, as shown in Table 1, in attempts to develop a reproducible procedure. To optimize the effort, the first screening among the above methods was based on reproducing a uniform distribution of catalyst and fines along the bed as observed in a wall region by employing an acrylic clear reactor. Pressure-drop measurements for single-phase (gas flow only) and both pressure drop and liquid holdup measurements for two-phase flow were used to quantify the reproducibility.

Visual observation of the wall region, as well as measuring the ratio of fines and catalyst along the bed by cutting 3 cm lengths of the reactor at different axial positions, were used to assess the uniformity of the packing. Table 2 contains the characteristics of the packing and reactor used. Catalyst/fines distribution has been measured at different axial positions by packing the reactor according to the procedures summarized in Table 1. By cutting the tube into pieces of 3 cm length and drying and separating the catalyst and fines, the volumetric ratio of fines to catalyst can be determined along the bed. These experiments show that the dry packing procedures A and B, where the volume of fines added just fills the voidage volume of the actual bed, produce a uniform and reproducible catalyst/fines distribution along the bed. These procedures were found to reproduce the fines/catalyst distribution along the different axial positions within a relative difference of 2% (the ratio of fines volume to catalyst volume at top, middle, and bottom of the diluted bed are 0.72, 0.73, and 0.72, respectively).

Table 1. Methods Tested for Packing a Bed with a Mixture of Catalyst and Fines

type	vol of fines just fill the bed voidage of catalyst particles	2 vol of fines to 1 vol of catalyst
I. dry method	(A) packing a portion of catalyst then a portion of fines with tapping or vibrating according to the developed procedure A	(C) packing a portion of 1 vol of catalyst then a portion of 2 vol of fines with tapping or vibrating
	(B) packing the whole bed with catalyst followed by the required amount of fines with tapping and vibrating according to the developed procedure B	(D) mixing a portion of 2 vol of fines with a portion of 1 vol of catalyst and pouring the mixture into the reactor
II. wet method	(E) mixing portion of catalyst with required portion of fines in the presence of a solvent until the mixture becomes as uniform as possible then introducing the mixture part by part with pressing each part inside the bed	(G) mixing a portion of 2 vol of fines and 1 vol of catalyst in the presence of a solvent until the mixture becomes as uniform as possible then introducing the mixture part by part with pressing each part inside the bed
	(F) same as E without pressing each introduced part	(H) same as G without pressing each introduced part

Table 2. Packed Bed Characteristics Used To Assess the Packing Uniformity of the Methods Listed in Table 1

reactor/packing	characteristics
reactor	inside diameter = 0.95 cm, 1.59 cm, 2.22 cm
optically clear acrylic packing	height = 57 cm, 200 cm
extrudate	size: 0.143 cm × 0.614 cm, 0.157 cm × 0.43 cm
sphere	diameter = 0.1 cm, 0.152 cm, 0.17 cm, 0.3 cm
fines	
nonporous	material: silicon carbide diameter = 0.021 cm bulk density = 1.51 g/cm ³ material density = 3.21 g/cm ³

All other methods failed to reproduce such uniformity. Dry methods (C) and (D) of Table 1 create clearly observed segregation of fines. Wet method of packing, using a slurry of fines and catalyst with subsequent pressing of the bed, yields nonuniform and nonreproducible fines and catalyst distribution along the bed (either regions with more catalyst or regions with more fines). If the bed is not pressed, the nonuniformity becomes worse. In case of the high volumetric ratio of fines to catalyst, as some investigators recommend, the results obtained with the wet method are marginally better than that obtained with the dry method but uniformity or reproducibility are not achieved. In addition, in the wet packing method one cannot always use the solvent at room temperature and in an open environment which makes the method inconvenient.

Table 3. Packed Bed Characteristics Used for Quantifying the Reproducibility in Pressure Drop and Liquid Holdup of the Developed Procedure

reactor	characteristics	method
Single-Gas Flow		
diluted bed		
optically clear acrylic		
fines: silicon carbide ($d_f = 0.021$ cm)		
spherical particles		
$d_r = 0.95$ cm	$d_p = 0.17$ cm, $f/c = 0.7$, $Z = 57$ cm, $\epsilon_{Bf} = 0.19$	whole bed packing procedure B
$d_r = 1.59$ cm	$d_p = 0.17$ cm, $f/c = 0.63$, $Z = 57$ cm, $\epsilon_{Bf} = 0.194$	whole bed packing procedure B
$d_r = 2.22$ cm	$d_p = 0.17$ cm, $f/c = 0.625$, $Z = 57$ cm, $\epsilon_{Bf} = 0.22$	developed procedure A and B
$d_r = 2.22$ cm	$d_p = 0.17$ cm, $f/c = 0.62$, $Z = 57$ cm, $\epsilon_{Bf} = 0.346$	wet bed packing procedure E
extrudate particles		
$d_r = 0.95$ cm	size = (0.143 × 0.614) cm, $f/c = 0.78$, $Z = 57$, $\epsilon_{Bf} = 0.16$	portion-by-portion procedure A
Two-Phase Flow		
diluted bed		
stainless steel		
fines: silicon carbide ($d_f = 0.021$ cm)		
extrudate particles		
$d_r = 1.55$ cm	size = (0.157 × 0.43) cm, $f/c = 0.61$, $Z = 56$, $\epsilon_{Bf} = 0.2$	portion-by-portion procedure A
$d_r = 2.2$ cm	size = (0.157 × 0.43) cm, $f/c = 0.54$, $Z = 56$, $\epsilon_{Bf} = 0.22$	portion-by-portion procedure A
nondiluted bed		
stainless steel		
extrudate particles		
$d_r = 2.2$ cm	size = (0.157 × 0.43) cm, $Z = 52$, $\epsilon_B = 0.36$	catalyst is packed portion by portion with tapping

The following is the step-by-step procedures developed to pack the diluted bed reproducibly by dry methods A and B of Table 1.

A. Portion of Catalyst by Portion of Fines Packing Procedure.

- (1) Use dry catalyst and fines.
- (2) Load the reactor with the known amount of catalyst to be utilized and determine the bed height.
- (3) Calculate the catalyst bed void volume based on the catalyst amount in step 2.
- (4) Discharge the catalyst.
- (5) Calculate the amount of fines which is required to just fill all the bed voidage volume as

$$\text{weight of fines required} = \text{bed void volume} \times \text{fines bulk density}$$

- (6) Divide the amount of catalyst and fines into portions. The number of portions (i.e., amount of each portion) was found not to be critical. The user can choose a number of portions based on convenience. In this study a 5–10 cm catalyst bed length was packed at a time.

- (7) Load a portion of the catalyst to the reactor. Gently tap or vibrate the reactor until the catalyst bed settles. The duration of the vibrating or tapping period was found not to be critical. A few minutes is adequate.

- (8) Load a portion of fines to the reactor. Vibrate or tap the bed gently, which qualitatively means maintaining the original bed of catalyst as stable as possible while the fines migrate to fill its voids. Tapping/

vibrating is continued until the top layer of the catalyst becomes visible. It is critical to detect this since when the tapping/vibrating period exceeded the time of the appearance of the catalyst layer at the top segregation occurred. Therefore in case of a stainless steel tube, which is frequently used in practice, a light source and/or optical fiber can be utilized to observe the bed surface.

(9) Repeat steps 7 and 8 until the total amount of catalyst and fines are packed. It should be noted that tapping/vibrating of the next portion of catalyst and/or fines does not lead to segregation of previous loaded portions (if tapping/vibrating is kept as qualitatively described in step 8 above). This is because the new portion of fines migrates to fill the voidage above the previous loaded mixture.

Note: The expansion in the bed height due to the addition of fines and tapping is within 2%.

B. Whole Bed Packing Procedure. In a long stainless steel reactor with small inside diameter it is very difficult to observe the top surface of a short bed at the bottom with the help of a light source. Moreover, an optical fiber is not always available for this purpose. Therefore, a new procedure of packing the whole bed was utilized and tested. This seemed promising based on the finding of step 6 of the developed procedure A that the number of portions used are not critical. Such procedure overcomes the difficulties associated with monitoring the catalyst surface at the reactor bottom. In contrast, the catalyst surface at the upper part of the reactor can be easily observed. The step-by-step procedure is as follows: (1) Follow step 1–5 of procedure A. (2) Load the amount of catalyst required portion by portion with associated tapping/vibrating. This is recommended to make the bed stable and reproducible. (3) Load all fines into the reactor. If there is not enough room to hold all the calculated amount of fines, load it portion by portion. Tap/vibrate until all the fines migrate into the bed and the top catalyst layer becomes visible.

Note: (1) On the basis of whether there is adequate room to accommodate fines at the top of the reactor, the catalyst bed can be loaded in two portions. The first portion is the major one which gives a suitable volume to load the fines into it and helps in observing easily the top of the catalyst surface. (2) The expansion in the bed height due to the addition of fines and tapping is little less than that of procedure A but in both procedures A and B the expansion is within 2%. (For example, in a 50 cm bed, the expansion obtained with procedure A is about 1 cm while with procedure B is about 0.7 cm.)

Reproducibility of the Developed Procedures

Pressure drop and liquid holdup measurements were used to quantify the reproducibility of the developed procedure to pack a laboratory reactor with a mixture of catalyst and fines. For this purpose, silicon carbide fines of 0.021 cm diameter, different catalyst shapes and sizes and different reactor diameters have been utilized as shown in Table 3. Figure 3 demonstrates the reproducibility of the measured pressure drop with gas flow only in a diluted bed packed three times by both procedure A and B. A comparison of pressure drop reproducibility between the developed procedure A and the wet method E is illustrated in Figure 4. In the wet method the bed was dried completely before performing a single-gas phase-flow experiment. The results reveal that the wet method failed to produce a reproducible pressure drop due to the nonuniform fines/catalyst

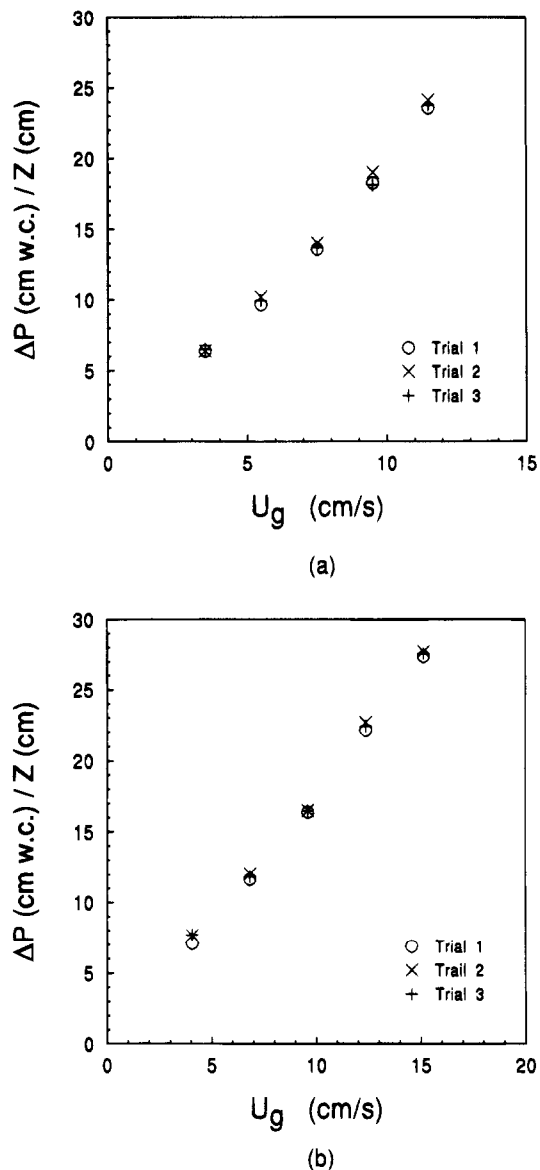
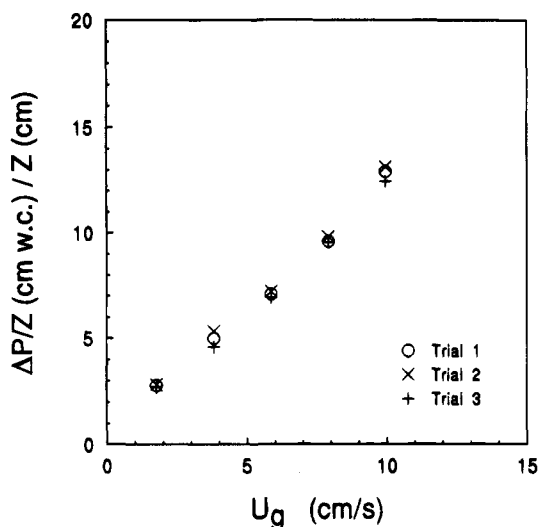


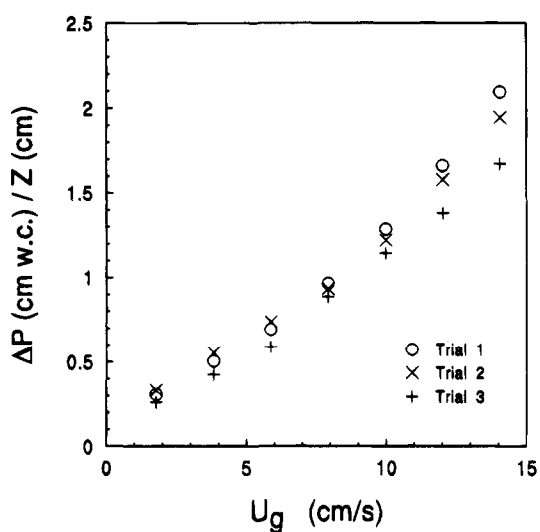
Figure 3. Reproducibility of pressure drop using gas-phase flow in a diluted bed packed by the developed procedures A and B. Fines: silicon carbide ($d_f = 0.21$ mm); pressure: 0.31 MPa (30 psig). Error bars are contained within the points. (a) Portion by portion packing (A). Gas, nitrogen; catalyst, extrudate (0.143×0.614 cm); volume fines/volume catalyst = 0.78; $\epsilon_{BF} = 0.16$; reactor, acrylic ($d_r = 1.59$ cm). (b) Whole bed packing (B). Gas, nitrogen; catalyst, sphere ($d_p = 0.17$ cm); volume fines/volume catalyst = 0.7; $\epsilon_{BF} = 0.19$; reactor, acrylic ($d_r = 0.95$ cm).

distribution along the bed which is not reproducible either. Also the bed height obtained using the same amount of catalyst and fines is higher than that obtained by the developed dry packing procedure which causes larger bed voidage. This results in lower pressure drop as shown in Figure 4b. Figure 5 illustrates the comparison of the pressure drop measured in three different reactor sizes packed by the developed procedure B with the same mixture of catalyst and fines. The pressure drop in the smallest reactor ($d_r = 0.95$ cm) is slightly higher than that of the others. This is because for smaller diameter reactors, the bed voidage close to the wall is higher. As a result the volumetric ratio of fines to catalyst required to fill its voidage is larger. Therefore, the smallest reactor has the largest fraction of fines and the lowest voidage which causes higher pressure drop. This is the cause of the higher pressure drop reported in Figure 2b than that in Figure 3a.

In practice, two-phase flow operation is of interest. Therefore, the reproducibility of the developed procedure



(a)



(b)

Figure 4. Comparison between the reproducibility of the developed procedure A and wet method E in pressure drop measurements using gas-phase flow only. Fines: silicon carbide ($d_f = 0.21$ mm); pressure, 0.31 MPa (30 psig); error bars are contained within the points. (a) Portion by portion dry packing (A). Gas, nitrogen; catalyst, sphere ($d_p = 0.17$ cm); volume fines/volume catalyst = 0.62; $\epsilon_{Bf} = 0.22$; reactor, acrylic ($d_r = 2.2$ cm). (b) Wet method packing (E). Gas, nitrogen; catalyst, sphere ($d_p = 0.17$ cm); volume fines/volume catalyst = 0.62; $\epsilon_{Bf} = 0.346$; reactor, acrylic ($d_r = 2.2$ cm).

has also been quantified in terms of both pressure drop (the ratio of frictional pressure drop to the liquid hydrostatic pressure, dimensionless pressure drop) and liquid holdup measurements. Pressure drop in single-phase gas flow and two-phase flow is measured by an accurate high-pressure differential pressure transducer. Liquid holdup is measured by the draining method (Al-Dahhan, 1993). To prevent hysteresis effects in the measured pressure drop, prior to each two-phase flow experiment, the packed bed after being extensively prewetted by soaking the bed and leaving it soak overnight, is operated first in the high interaction regime at high liquid mass velocities. Then these velocities are reduced to the desired level at which the pressure drop and liquid holdup are measured. This procedure is recommended for the bed without fines to prevent hysteresis effects in measured pressure drop and is also utilized for diluted beds in this study. Figure 6 confirms the reproducibility achieved by the developed

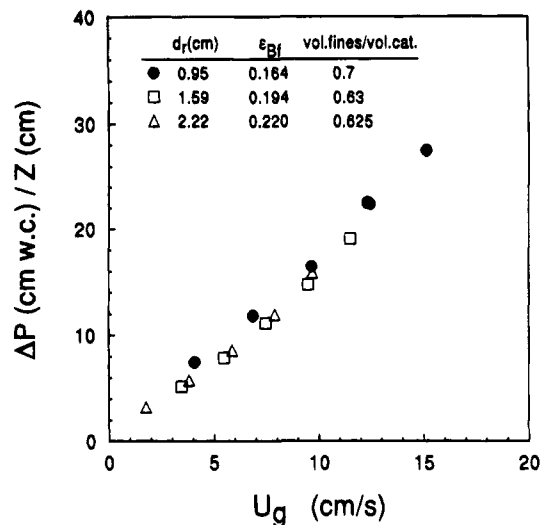


Figure 5. Comparison of pressure drop in different reactor sizes packed by the developed procedure B (whole bed packing procedure) with the same mixture of catalyst and fines. Gas, nitrogen; catalyst, sphere ($d_p = 0.17$ cm); fines, silicon carbide ($d_f = 0.21$ mm); pressure, 0.31 MPa (30 psig). The points represent the average of three experiments with error bars contained within the points.

procedure A in two-phase flow operation within 5% experimental error. The effect of the extent of bed dilution on pressure drop and liquid holdup is shown in Figure 7 which compares the dimensionless pressure drop and liquid holdup in a bed packed by the developed procedure (fines just fill its voidage) and in a bed packed by wet method (G) with a mixture ratio of two volume of fines to one volume of catalyst. At constant liquid mass velocity and gas superficial velocity, pressure drop is higher and liquid holdup is lower in the bed packed by the developed procedure compare to the bed packed with two volume fines to one volume catalyst. This is due to lower voidage in the first bed where more solid retards the flow of fluid that causes more energy dissipation (higher pressure drop), while more fines in the second bed provide more solid to solid points for liquid to flow over which increases liquid holdup.

Closing Remarks

The developed dry method of packing laboratory-scale trickle-bed reactors with a mixture of catalysts and fines yields uniformity in the fines/catalyst distribution along the bed and the desired reproducibility in measured pressure drop and liquid holdup. This makes the kinetic data obtained in such reactors meaningful and useful for either scale-up or scale-down. The wet method, where the catalyst is mixed with fines as a slurry before they are loaded to the reactor, does not produce a uniform packing or reproducible pressure drop. For a highly diluted bed as some investigators used, either the wet method or dry method of packing does not produce uniformity in catalyst/fines distribution. Moreover, in the wet method, a suitable solvent cannot always be found to be used at room temperature and in an open environment which makes the method inconvenient. Hence, using a larger ratio of fines to catalyst than required to fill the bed voids is not necessary and will not necessarily result in reproducible packing.

Al-Dahhan and Duduković (1993) recently found that the catalyst wetting efficiency is related strongly to both pressure drop and liquid holdup. Hence, producing reproducibility in these parameters (pressure drop and liquid holdup) would enhance the reproducibility in

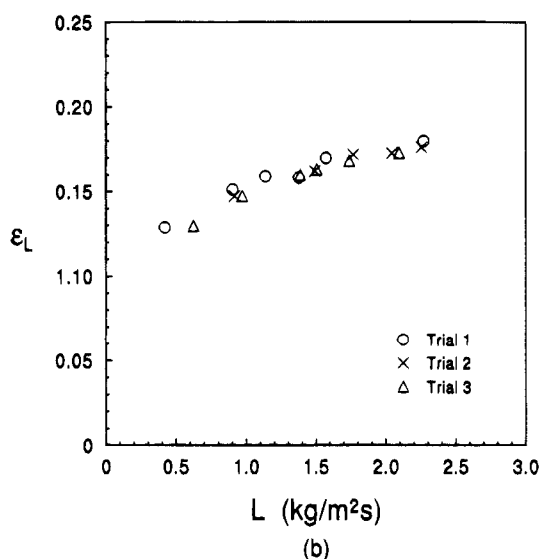
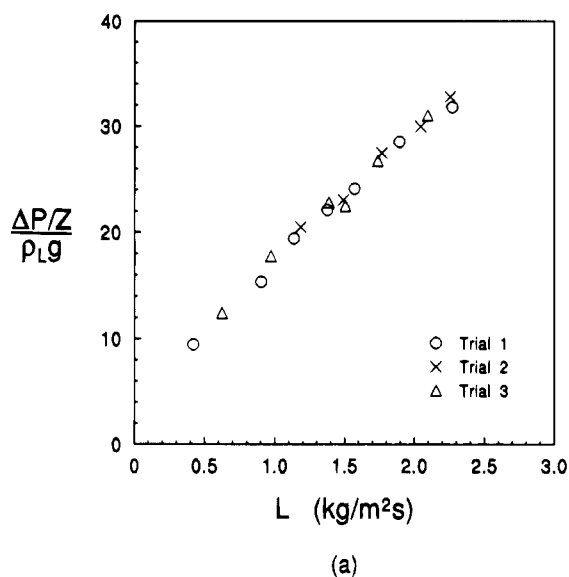


Figure 6. Reproducibility of pressure drop and liquid holdup achieved by the developed procedure A in two-phase flow operation. System, hexane/nitrogen; catalyst, 0.5% Pd extrudate (0.157×0.43 cm); fines, silicon carbide ($d_f = 0.21$ mm); volume fines/volume catalyst = 0.61; $\epsilon_{BF} = 0.2$; reactor, stainless steel ($d_r = 1.55$ cm); pressure, 0.31 MPa (30 psig); gas superficial velocity, 4 cm/s.

catalyst wetting efficiency and catalyst utilization. However, further work is recommended to test the reproducibility of the developed procedure on the catalyst utilization and wetting efficiency by employing a liquid-limited test reaction and for pressure drop and liquid holdup over a wide range of operating conditions (such as reactor pressure, gas and liquid superficial velocities, etc.). It should be noted that fines with good thermal conductivity are also used in laboratory and pilot plant testing to provide good heat transfer and better temperature uniformity in the reactor bed, especially when reaction are highly exothermic. In these situations, the developed procedure would produce better and reproducible temperature uniformity since catalyst and fines are distributed uniformly and reproducibly compared to highly diluted bed (e.g., two volume fines to one volume catalyst or more) packed by wet method as discussed earlier where neither a uniform distribution of catalyst and fines nor reproducibility are obtained. Moreover, higher pressure drop and lower liquid holdup in the diluted bed packed by the developed procedure compared to the bed diluted by two volumes

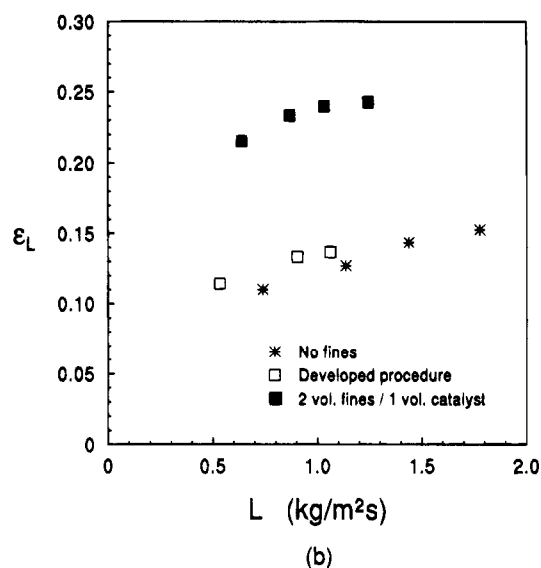
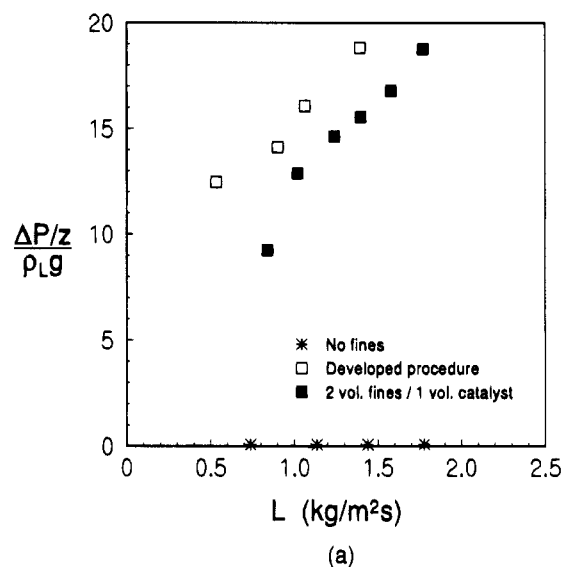


Figure 7. Comparison among pressure drop and liquid holdup obtained in a nondiluted bed of extrudates, diluted bed packed by the developed procedure A (volume fines/volume catalyst = 0.54) and diluted bed with volume fines/volume catalyst = 2 packed by wet method G. Pressure, 0.31 MPa (30 psig); gas superficial velocity = 1 cm/s.

of fines to one volume of catalyst (Figure 7) would provide better liquid distribution, heat transfer, and temperature uniformity (Al-Dahhan and Duduković, 1993).

Acknowledgment

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Nomenclature

d_p = particle diameter of the spherical particle, cm
 $(d_p)_{eq}$ = equivalent diameter of the cylindrical particle, cm
 d_r = reactor diameter, cm
 f/c = ratio of volume fines to volume catalyst
 g = gravitational acceleration, cm/s²
 G = superficial gas mass velocity, kg/m² s
 L = superficial liquid mass velocity, kg/m² s
 P = operating pressure, MPa
 $\Delta P/Z$ = pressure drop per unit bed length, g/cm² s²
 U_g = superficial gas velocity, cm/s
 Z = packed-bed length, cm

$(\Delta P/Z)/\rho_L g$ = dimensionless pressure drop, the ratio of frictional pressure drop to the liquid hydrostatic pressure

Greek Letters

ϵ_B = nondiluted bed void per reactor volume (bed porosity)

ϵ_{Bf} = diluted bed void per reactor volume

ϵ_L = external liquid holdup per reactor bed volume ($\epsilon_{Ld} + \epsilon_{Ls}$)

ϵ_{Ld} = dynamic liquid holdup per reactor volume

ϵ_{Ls} = static liquid holdup per reactor volume

ρ_L = liquid density, g/cm^3

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