Prediction of bed voidage in multi-phase fluidized bed using Air/Newtonian and non-Newtonian liquid systems

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\textbf{A B S T R A C T}

In general, multiphase reactors with different configurations are used in various industries, a fluidized bed reactor has found extensive application in wastewater treatment and other biochemical processes. For the design and development of three-phase fluidized bed reactors, knowledge of the hydrodynamic parameters such as bed voidage is essential. In this paper, an attempt has been made using water, glycerol with different concentrations, and mono ethanolamine as Newtonian liquid and different concentrations of carboxy methyl cellulose as non-Newtonian liquids and seven different particles to study the effect of fundamental and operating variables on bed voidage in a three-phase fluidized bed. The dependency of the bed voidage on various parameters such as the gas and liquid flow rates, particle size and shape, and the physical and rheological properties of liquids are analyzed. The bed voidage increases with fluid flow rates and decreases with an increase in particle diameter and sphericity and it increases with an increase in the viscosity of Newtonian liquids and fluid consistency index of non-Newtonian liquids. On the basis of the experimental results, a generalized correlation has been developed to predict bed voidage in a fluidized bed using Newtonian and non-Newtonian liquids. The experimental results showed good agreement with those predicted according to the developed correlation, with a wide range of operating conditions.

\textit{Keywords:} Bed voidage; Fluidized beds; Hydrodynamics; Multiphase reactors; non-Newtonian liquids

1. Introduction

The operating modes of three-phase contactors used in industry can be broadly classified under two categories viz., (i) the solid particles in a fixed state (packed bed), and (ii) the solid particles in a suspended state (fluidized bed). The choice of the position of solids depends mainly on the nature of the reaction system. Though three-phase contactors with varying configurations are used in industry, fluidized bed reactor is preferred for many chemical engineering operations, namely, catalytic hydrogenation, hydro-cracking, coal liquefaction, hydro-desulphurization of petroleum fraction, etc., because it offers high mass transfer rates as a result of good mixing [1–4]. Recently, it gained importance in the area of the biotechnological process such as fermentation and aerobic wastewater treatment applications, where bacteria or enzymes are entrapped within porous particles or immobilized on the surface of the inert solids [5]. The industrial effluent is fed into the fluidized bed reactor at a given superficial fluid velocity enough to suspend the support media. The suspended support media are powerfully agitated by the fluid passing through the bed, great mixing is obtained. The main use of the fluid-fluid distributor is to uniformly distribute the wastewater across the
reactor bed. The fluidized media may be an immobilized cata-
ylist in the advanced oxidation process and microorganisms
in the biological treatment process. Sometimes, recycling of
treated wastewater may be carried out in order to enhance
the removal efficiency.

The applications of embedded anaerobic fluidized bed
membrane bioreactor for effluent treatment and resulted
in minimum energy consumption and lowered membrane fouling.
Some of the excellent features of fluidized bed reactor (FBR) are low operating cost, high resistance to sys-
tem upsets, excellent mixing, high mass transfer rates, and
low sludge production, etc. [5,6]. Apart from this, if solid
particles are used as catalysts, they can be easily added
or withdrawn from the reactor for regeneration. Besides,
wastewater which contains more organic matter can be
treated by aerobic methods or by anaerobic digestion in
fluidized bed reactors or up-flow anaerobic sludge blanket
reactors (UASBR). The microbial electrochemical-fluidized bed
reactor (ME-FBR) is a single compartment reactor and
is comparatively quite easy to perform. In ME-FBRs, the
anode behaves in a fluid-like state and it has some advan-
tages such as good electron acceptor, high surface area and
carrier for biomass growth which in turn minimize the
cells wash-out, higher mass and temperature transport,
along with good mixing within the fluidized bed reactor
[7]. Various research aspects such as the movement of elec-
trodes, stirred conductive granules, capacitive conductive
granules, operating different modulated units in parallel
or serial in order to improve treatment efficiency are cur-
cently performed. However, this type of reactor may not be
cost-effective to treat large volumes of industrial effluent [7].

The challenges like exploiting the present infrastruc-
tures of effluent treatment plants (the fluidized bed con-
figurations) in the design of the reactor can be removed by
implementing bio-electrochemical effluent treatment along
with significant investments. The recent developments in
the treatment of industrial effluent are hybrid microbial
electrochemical technologies, membrane bioreactor-micro-
bial fuel cells, and hybrid systems based on the combination
of electrocoagulation with various biological reactors [7].
The successful scale-up, design, and operation of fluidized
beds mainly depend upon the accurate prediction of the
behavior and features of the system such as bed voidage.
The pioneering work was initiated by Richardson and Zaki
[1] and then many investigators made significant contribu-
tions toward bed voidage in fluidized beds [8–10]. Further,
it was also observed that most of the authors developed bed
voidage correlations using Newtonian liquids only [11–16].
The availability of bed voidage correlations using non-Newton-
ian liquids is limited. Since many biochemical reaction fluids
behave as power-law non-Newtonian liquids [17–25], there
is a vital need to obtain data with a wide range of variables
using non-Newtonian liquids and to develop generalized
representation for the correlating the data. Hence, an attempt has
been made using water, various concentrations of glycerol
and mono ethanol amine (MEA) as Newtonian liquid and
different concentrations of carboxy methyl cellulose (CMC)
as non-Newtonian liquids and different solid particles to
study the influence of fundamental and operating variables
on bed voidage in a three-phase fluidized bed. The main

2. Experimental setup and procedure

All experiments were carried out in a Perspex column
(0.15 m inner diameter and 1.8 m height) [15,17]. The exper-
imental column had a provision to feed the gas and liquid
at the base of the reactor. Using a centrifugal pump, liquid
from the storage tank was pumped into the reactor through
the gas–liquid distributor. Calibrated rotameters were used for
the measurement of both gas and liquid flow rates with an
accuracy of ±2%. The liquid phase flowed through a cal-
ming section of 0.1 m height filled with 0.0048 m Raschig
rings and entered the bed through a wire screen, support-
ing the particles. Compressed air was fed into the bottom
of the column through a pressure regulating valve. A gas
distributor was provided at the bottom of the fluidized col-
umn. The gas–liquid distributor’s design details are found
in previous works [15,17,19]. Water, different concentra-
tions of glycerol, and MEA are Newtonian liquid systems
and different concentrations of CMC, are non-Newtonian
liquids and seven different particles were used. The details
of the characteristics of different fluids and solids used
in the present study are mentioned in Table 1. The bed
voidage was determined by measuring the bed height [16].
The bed voidage ($\varepsilon$) is represented as:

$$\varepsilon = (\varepsilon_s + \varepsilon_g) = 1 - \varepsilon_r,$$

where the mean hold-up of solids in the bed was calculated
based on the weight of dry particles and height of the fluid-
ized-bed column by:

$$\varepsilon_r = \frac{M_{w, A}}{\rho_A h}.$$  

A minimum of 3–5 readings were taken and the aver-
age value was used for calculations and the reproducibility
of the errors was found to be within ±2%.

3. Results and discussion

3.1. Effect of superficial fluid velocities on bed voidage

The bed voidage is found to vary with respect to the fun-
damental and operating variables. In three-phase fluidiza-
tion process, it was found that bed voidage depends upon the
gas and liquid flow rates. Fig. 1 shows the effect of superficial
gas and liquid flow rates on bed voidage for spherical par-
cles ($d_s = 0.004 m$). As evident from Fig. 1, for any given
constant liquid flow rate, the bed voidage increases with an
increase in gas flow rates. Similarly, for any fixed gas flow rate, when the liquid flow rate increases, the bed voidage increases. However, at low gas superficial velocities (0.009–0.043 m/s), the effect is not significant. This may have been due to the low preliminary value of the expansion of the bed. From the experimental results, we found that when gas was introduced, for the smaller size particles (1 and 2 mm glass beads) less significant initial contraction in bed voidage was observed which is in concurrence with the literature [8,16]. At high gas superficial velocities (0.06–0.095 m/s) there was a rapid increase in bed voidage. This is because of the larger drag forces applied to the solid particles by an increase in the liquid superficial velocity causing the solid bed to expand.

3.2. Effect of particle diameter and sphericity on bed voidage

The effect of particle diameter on bed voidage can be seen in Fig. 2. It may also be observed that the bed voidage decreases with increasing particle diameter and decreases with increasing sphericity of particle which is shown in Fig. 3, for given constant gas and liquid flow rate. Bed voidage decreases with increasing particle diameter as well as decreasing particle sphericity and mainly due to the bubble wakes of large bubbles present at the bottom of the particle which resists the solid particle from expanding.

3.3. Effect of physical and rheological properties of liquids on bed voidage

The dependency of the bed voidage on the liquid properties was analyzed using eight different liquid systems (water, 20% glycerol, 60% glycerol, 90% glycerol, MEA, 0.1% CMC, 0.5% CMC, and 1% CMC). The bed voidage increases with increasing viscosity of Newtonian liquids (Fig. 4) and fluid consistency index (k) of non-Newtonian liquids (Fig. 5). Increasing fluid consistency index of the CMC solutions increases shear force between the liquid–solid interfaces, thus leading to an increase in bed voidage.

3.4. Improved correlation for bed voidage

The predictive ability of the important available literature correlations (Table 2) was compared with the present data and literature data. The statistical analysis of the present experimental and literature data on bed voidage (Table 3) shows that most of the literature correlations are restricted to the individual author’s own range of data. A few researchers have failed to consider the effect of particle characteristics and rheological properties of the fluids such as flow consistency index (k) on bed voidage [8,11] and hence those

![Fig. 1. Effect of liquid and gas velocities on bed voidage.](image)

| Details of particles and liquid system used in the present work for bed voidage |
|-----------------|-----------------|-----------------|-----------------|
| Bed characteristics | $d_p$ (m) | $\rho$ (kg/m$^3$) | $\phi_s$ | $d_l$ (m) |
|-----------------|-----------------|-----------------|-----------------|
| Particle 1 | Spheres | 0.001 | 2,480 | 1 | 0.15 |
| Particle 2 | Spheres | 0.002 | 2,480 | 1 | 0.15 |
| Particle 3 | Spheres | 0.004 | 2,480 | 1 | 0.15 |
| Particle 4 | Spheres | 0.0055 | 2,480 | 1 | 0.15 |
| Particle 5 | Spheres | 0.0072 | 2,480 | 1 | 0.15 |
| Particle 6 | Berl saddles | 0.0048 | 2,050 | 0.33 | 0.15 |
| Particle 7 | Raschig rings | 0.0051 | 2,480 | 0.58 | 0.15 |

Properties of fluids

<table>
<thead>
<tr>
<th>Density (kg/m$^3$)</th>
<th>Viscosity (kg/m/s)</th>
<th>Surface tension (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>System 1</td>
<td>Water</td>
<td>1,000</td>
</tr>
<tr>
<td>System 2</td>
<td>20% Glycerol</td>
<td>1,010</td>
</tr>
<tr>
<td>System 3</td>
<td>60% Glycerol</td>
<td>1,020</td>
</tr>
<tr>
<td>System 4</td>
<td>90% Glycerol</td>
<td>1,040</td>
</tr>
<tr>
<td>System 5</td>
<td>MEA</td>
<td>1,050</td>
</tr>
<tr>
<td>System 6</td>
<td>0.1% CMC</td>
<td>1,020</td>
</tr>
<tr>
<td>System 7</td>
<td>0.5% CMC</td>
<td>1,020</td>
</tr>
<tr>
<td>System 8</td>
<td>1% CMC</td>
<td>1,020</td>
</tr>
</tbody>
</table>
correlations predict results with higher deviation for both present and literature data [8–10]. Graphical analysis of the present data shows that the variation of bed voidage can be attributed to the effect of all the above-said variables.

In this study, the approach of the dimensionless method was adopted for the establishment of bed voidage correlations. The combined effects of the liquid properties were accommodated using Modified Morton’s number. Regression analysis of the experimental and available literature data (Table 3), obtained by using nineteen liquid systems with 25 different particles, gave the constants and indices for the bed voidage correlation as given below:

\[
\varepsilon = 0.9 \left( Fr \right)^{0.09} \left( 1 + Fr \right)^{0.6} \left( Mo_{v,m} \right)^{0.07} \left( \frac{\rho}{\rho_l} \right)^{0.05} \left( \frac{d_p}{d_0} \right)^{0.01} \left( \phi \right)^{0.07}
\]  

(3)

Using the proposed correlation (Eq. (3)), statistical error analysis has been performed and obtained an absolute average relative deviation (AARD) of ±8.8% for bed voidage indicating a satisfactory representation of the available data for air-Newtonian and air-non-Newtonian systems. The applicability of the present correlation has been tested with the available literature’s bed voidage data [8–10], which shows a satisfactory agreement (Table 4).

4. Conclusion

In a three-phase fluidized bed, the dependency of bed voidage on various operating and fundamental variables with a wide range has been analyzed. A dimensionless correlation for the prediction of bed voidage has been developed and its applicability has been analyzed using the present experimental data along with those of published literature sources covering a wide range of variables. The statistical analysis confirmed that the predictive ability of the proposed correlation is good. Therefore, the proposed correlation can be confidently used for the estimation of the bed voidage, with the knowledge of the fundamental and operating variables.
Table 2
Details of literature data used for bed voidage analysis

<table>
<thead>
<tr>
<th>Bed characteristics</th>
<th>$d_p$ (m)</th>
<th>$\rho_s$ (kg/m$^3$)</th>
<th>$\phi_s$</th>
<th>$d_c$ (m)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass ballotini</td>
<td>0.00028</td>
<td>2.960</td>
<td>1</td>
<td>0.1016</td>
<td>[8]</td>
</tr>
<tr>
<td>Glass ballotini</td>
<td>0.00058</td>
<td>2.940</td>
<td>1</td>
<td>0.1016</td>
<td></td>
</tr>
<tr>
<td>Glass ballotini</td>
<td>0.0012</td>
<td>2.700</td>
<td>1</td>
<td>0.1016</td>
<td></td>
</tr>
<tr>
<td>Glass ballotini</td>
<td>0.002</td>
<td>2.880</td>
<td>1</td>
<td>0.0508</td>
<td></td>
</tr>
<tr>
<td>Glass ballotini</td>
<td>0.0022</td>
<td>2.500</td>
<td>1</td>
<td>0.1016</td>
<td></td>
</tr>
<tr>
<td>Spheres</td>
<td>0.0013</td>
<td>2.700</td>
<td>1</td>
<td>0.056</td>
<td>[9]</td>
</tr>
<tr>
<td>Spheres</td>
<td>0.00106</td>
<td>2.700</td>
<td>1</td>
<td>0.056</td>
<td></td>
</tr>
<tr>
<td>Spheres</td>
<td>0.002235</td>
<td>2.710</td>
<td>1</td>
<td>0.056</td>
<td></td>
</tr>
<tr>
<td>Spheres</td>
<td>0.003348</td>
<td>2.400</td>
<td>1</td>
<td>0.056</td>
<td></td>
</tr>
<tr>
<td>Spheres</td>
<td>0.00498</td>
<td>2.260</td>
<td>1</td>
<td>0.056</td>
<td></td>
</tr>
<tr>
<td>Spheres</td>
<td>0.005</td>
<td>2.707</td>
<td>1</td>
<td>0.056</td>
<td></td>
</tr>
<tr>
<td>Spheres</td>
<td>0.006</td>
<td>2.300</td>
<td>1</td>
<td>0.66</td>
<td>[10]</td>
</tr>
<tr>
<td>Spheres</td>
<td>0.001</td>
<td>2.950</td>
<td>1</td>
<td>0.66</td>
<td></td>
</tr>
</tbody>
</table>

Properties of fluids

<table>
<thead>
<tr>
<th></th>
<th>Density (kg/m$^3$)</th>
<th>Viscosity (kg/m/s)</th>
<th>Surface tension (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>680</td>
<td>0.00036</td>
<td>1</td>
</tr>
<tr>
<td>Water</td>
<td>995</td>
<td>0.00085</td>
<td>1</td>
</tr>
<tr>
<td>Kerosene</td>
<td>800</td>
<td>0.00117</td>
<td>1</td>
</tr>
<tr>
<td>0.17 wt.% CMC</td>
<td>1,002</td>
<td>0.02</td>
<td>0.916</td>
</tr>
<tr>
<td>0.35 wt.% CMC</td>
<td>1,001</td>
<td>0.07</td>
<td>0.914</td>
</tr>
<tr>
<td>25 wt.% Sugar</td>
<td>1,090</td>
<td>0.00237</td>
<td>1</td>
</tr>
<tr>
<td>42 wt.% Sugar</td>
<td>1,170</td>
<td>0.0076</td>
<td>1</td>
</tr>
<tr>
<td>40 vol.% Acetone</td>
<td>960</td>
<td>0.00143</td>
<td>1</td>
</tr>
<tr>
<td>Water</td>
<td>1,000</td>
<td>0.0011</td>
<td>1</td>
</tr>
<tr>
<td>0.1 wt.% CMC</td>
<td>1,004</td>
<td>0.0063</td>
<td>0.971</td>
</tr>
<tr>
<td>0.17 wt.% CMC</td>
<td>1,002</td>
<td>0.02</td>
<td>0.916</td>
</tr>
<tr>
<td>36 wt.% Sugar</td>
<td>1,150</td>
<td>0.00464</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3
List of important literature correlations for bed voidage

<table>
<thead>
<tr>
<th>Author</th>
<th>Correlations</th>
<th>System</th>
<th>Range of variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Begovich and Watson [4]</td>
<td>$\varepsilon = 3.93\left(\mu_i^{0.05\phi_s}\right)^{0.271}\left(U_i\right)^{0.044}\left(U_g\right)^{0.044}\left(\rho_s - \rho_i\right)^{-0.356}\left(d_p - 0.268\left(d_i\right)^{-0.055}\right)\left(d_i\right)^{-0.053}$</td>
<td>Air–water</td>
<td>$d_i = 0.0046–0.0062$ m $\rho_i = 1.720–2.440$ kg/m$^3$ $U_i = 0–0.17$ m/s $U_g = 0–0.12$ m/s $d_p = 0.002–0.006$ m $\mu = 10$ to 120 MPa.s $\rho = 850–870$ kg/m$^3$</td>
</tr>
<tr>
<td>Nikov et al. [11]</td>
<td>$\varepsilon = \left(2.5 + 13.2\mu_i^{0.05\phi_s}\right)\left(U_i\right)^{0.274}\left(U_g\right)^{0.044}\left(\rho_s - \rho_i\right)^{0.336}\left(d_p - 0.268\left(d_i\right)^{-0.033}\right)$</td>
<td>Air–mineral oils and mixtures of Vitréa oils with kerosene</td>
<td>$d_i = 0–0.05$ m $U_i = 0–0.03$ m/s $U_g = 0.003–0.043$ m/s $\mu = 10$ to 120 MPa.s $\rho = 850–870$ kg/m$^3$</td>
</tr>
</tbody>
</table>
### Symbols

- $A$ – Cross-sectional area of bed, $m^2$
- $AARD$ – Absolute average relative deviation
- $Ar_i$ – Liquid Archimedes number, $\frac{g d_i^3 \rho_s^2}{\mu_i^3}$
- $Bias$ – Bias
- $Bo$ – Bond number, $\frac{g d_p^2 \rho_s}{\sigma}$
- $d_c$ – Column diameter, $m$
- $d_p$ – Particle diameter, $m$
- $Fr_g$ – Froude number of gas, $\frac{U_{i_g}^2}{g d_p}$
- $Fr_l$ – Froude number of liquid, $\frac{U_{i_l}^2}{g d_p}$
- $g$ – Acceleration due to gravity, $m/s^2$
- $h$ – Height of bed, $m$
- $k$ – Flow consistency index, $kg/m^3s^{-2}$
- $Mo_i$ – Morton number of liquid, $\frac{\mu_i^2 g}{\rho_i \sigma_i}$
- $Mo_{LM}$ – Modified Morton number of liquid, $\frac{We^3}{Fr_l N_{Re,LM}}$
- $M_s$ – Total solid mass in bed, $kg$
- $N$ – Number of data points
- $n$ – Fluid behavior index
- $N_{Ga}$ – Galileo number, $\frac{g d_p^2 \rho_s (\rho_s - \rho)}{\mu_i^3}$
- $N_{Re}$ – Reynolds’s number of liquid, $\frac{d_p U_i \rho_s}{\mu_i}$
- $N_{Re,LM}$ – Modified Reynolds’s number of liquid, $\frac{d_p U_i^2 \rho_s}{\mu_i} \frac{k}{k}$
- $U_i$ – Superficial gas velocity, $m/s$
- $U_{i,l}^l$ – Superficial liquid velocity, $m/s$
- $We_i$ – Weber number, $\frac{d_p \mu_i^2 \rho_s}{\sigma_i}$

### Greek

- $\rho_l$ – Liquid density, $kg/m^3$
- $\sigma_i$ – Liquid surface tension, $N/m$
- $\mu_i$ – Liquid viscosity, $kg/m/s$
- $\rho_s$ – Particle density, $kg/m^3$
- $\varepsilon_s$ – Solid holdup
- $\varepsilon$ – Voidage of bed
- $\phi_s$ – Sphericity of particle
- $\rho_g$ – Gas density, $kg/m^3$
- $\mu_g$ – Gas viscosity, $kg/m/s$

### Abbreviations

- AARD – Absolute average relative deviation
- CMC – Carboxy methyl cellulose
- MEA – Mono ethanol amine
- UASBR – Upflow anaerobic sludge blanket reactor
- ME-FBR – Microbial electrochemical-fluidized bed reactor

### References


