AN ABSTRACT OF THE THESIS OF

Frantz Villers for the degree of Master of Science in Chemical Engineering presented on January 29, 1998.

Title: Bed Porosity in a Magnetically Stabilized Liquid-Solid Fluidized bed.

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Goran Jovanovic

In this study, we investigate the behavior of a magnetically stabilized liquid-solid fluidized bed (MSFB) in an axial uniform and time-invariant magnetic field. The magnetic field is generated by a copper coil. Fields from zero to 26000 A/m are produced. Nine types of particles are used in this study with a mean diameter of 2mm, 2.5mm and 3mm, and a content of the ferromagnetic material of 10%, 20%, and 30% by weight. Water at room temperature is the fluidizing fluid.

The pressure drop through the bed is measured at seven locations along the fluidization column. The pressure drop data are used to evaluate the average bed porosity. The following equation was found to represent average bed porosity for any given fluidization:

\[ \frac{\varepsilon - \varepsilon_{ms}}{\varepsilon_{ff} - \varepsilon_{ms}} = \frac{H_{ms} - H}{H_{ff} - H_{ms}} \]

Magnetic properties of the particles, namely the magnetization M, play a major role in the behavior of the MSFB. Inclusion of the magnetic field strength in the above equation is the key to the modeling of average bed porosity. It allows the model to be applicable to different types of ferromagnetic particles, which is an improvement to previously found correlations.
\[ \varepsilon_{ms} = aH_{ms} + b . \]

The stability of particle structures depends on the balance of forces acting on particles at the onset of stabilization \((H_{ms}, U_{ms}, \varepsilon_{ms})\). We propose a correlation of \(H_{ms}\) versus particle Reynolds number as:

\[ H_{ms} = a(V_\%)^\nu (Re_{ms} - Re_{mf}) \]

which captures the influence of both attraction forces (caused by magnetization of particles) and dispersion forces (caused by fluid particle interaction).

A newly developed concept of virtual particle diameter is also proposed for the prediction of the bed porosity. This concept hinges on the application of the well known Richardson-Zaki equation often used for the prediction of the average bed porosity in ordinary liquid-solid fluidized beds. It was found that the bed average porosity data can be successfully modeled with this equation if the nominal particle diameter is replaced by virtual particle diameter. The size of the virtual particle diameter increases with magnetization of particles as expected and follow the correlation:

\[ d_p = d_{vp} + a_1 \times H^2 \]
Bed Porosity
in
a Magnetically Stabilized Liquid-Solid Fluidized Bed
by
Frantz Villers

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degree of

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# TABLE OF CONTENTS

CHAPTER 1 – INTRODUCTION

CHAPTER 2 - THEORETICAL BACKGROUND

2.1- Magnetically Stabilized Fluidized Bed (MSFB)

2.2- Pressure drop through the bed and minimum fluidization velocity

2.3- Porosity in a MSFB

2.4- Virtual diameter

CHAPTER 3 - APPARATUS

3.1- Fluidization column with particles

3.2- The water supply system

3.3- The pressure measuring system

3.4- The magnetic field generator

CHAPTER 4 - EXPERIMENTAL MEASUREMENTS

4.1- The overall pressure drop across the bed

4.2- Height of the bed

4.3- Porosity of the bed

CHAPTER 5 - EXPERIMENTAL RESULTS AND DISCUSSION

5.1- Average bed porosity

5.2- Particle virtual diameter
TABLE OF CONTENTS (CONTINUED)

CHAPTER 6 - CONCLUSION AND RECOMMENDATIONS 66

BIBLIOGRAPHY 68

APPENDICES 72

A- Magnetic field strength in a thin solenoid of finite length 73
B- Particles production 75
C- Voltage - current calibration curve for the magnetic field generator 78
D- Calibration of the orifice meter 79
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Qualitative phase diagram for MSFBs</td>
<td>4</td>
</tr>
<tr>
<td>2-2</td>
<td>Balance of forces; a) in a uniform magnetic field; b) in a non-uniform magnetic field</td>
<td>8</td>
</tr>
<tr>
<td>2-3</td>
<td>Particle arrangement in MSFB as a function of the magnetic field strength; a) Low magnetic field – random distribution of particles; b) High magnetic field – particles are associated in chains along the magnetic field lines and direction of field flow</td>
<td>12</td>
</tr>
<tr>
<td>2-4</td>
<td>Average bed porosity changes as a function of magnetic field strength for constant water superficial velocities for 1.8 mm diameter ferromagnetic particles from Honerez(1994)</td>
<td>10</td>
</tr>
<tr>
<td>2-5</td>
<td>Experimental measurement of the minimum fluidization velocity from Rosensweig(1979)</td>
<td>11</td>
</tr>
<tr>
<td>2-6</td>
<td>Porosity zones in a fluidized bed</td>
<td>14</td>
</tr>
<tr>
<td>2-7</td>
<td>Bed height determination for a non uniform bed porosity</td>
<td>15</td>
</tr>
<tr>
<td>2-8</td>
<td>a) Average bed porosity, and b) In ( \text{versus In} ) ((H)) (Eq. 2-4) plot from Kwauk (1992)</td>
<td>19</td>
</tr>
<tr>
<td>2-9</td>
<td>The concept of particle virtual diameter; a) random distribution of particles, b) under a magnetic field, particles associate in chains, c) particles associations are “seen” by the field as large particles with equivalent virtual particle diameter, d) decrease in bed height due to the increase in particle apparent (virtual) diameter</td>
<td>20</td>
</tr>
<tr>
<td>3-1</td>
<td>Experimental apparatus</td>
<td>23</td>
</tr>
<tr>
<td>3-2</td>
<td>Ferromagnetic composite particles</td>
<td>25</td>
</tr>
<tr>
<td>3-3</td>
<td>Experimental measurement of the minimum fluidization velocity</td>
<td>27</td>
</tr>
</tbody>
</table>
LIST OF FIGURES (CONTINUED)

4-1 The determination of the bed height ($\kappa=20\% w$ ferrite content) 30

4-2 Pressure drop in a bed with non uniform porosity distribution 33

5-1 Average bed porosity changes as a function of magnetic field intensity and water superficial velocity ($d_p=1.9\text{mm}$, $\kappa=10\%$) 36

5-2 Average bed porosity changes as a function of magnetic field intensity and water superficial velocity ($d_p=2\text{mm}$, $\kappa=20\%$) 37

5-3 Average bed porosity changes as a function of magnetic field intensity and water superficial velocity ($d_p=2\text{mm}$, $\kappa=30\%$) 38

5-4 Average bed porosity changes as a function of magnetic field intensity and water superficial velocity ($d_p=2.5\text{mm}$, $\kappa=10\%$) 39

5-5 Average bed porosity changes as a function of magnetic field intensity and water superficial velocity ($d_p=2.5\text{mm}$, $\kappa=20\%$) 40

5-6 Average bed porosity changes as a function of magnetic field intensity and water superficial velocity ($d_p=2.6\text{mm}$, $\kappa=30\%$) 41

5-7 Average bed porosity changes as a function of magnetic field intensity and water superficial velocity ($d_p=3\text{mm}$, $\kappa=10\%$) 42

5-8 Average bed porosity changes as a function of magnetic field intensity and water superficial velocity ($d_p=3.1\text{mm}$, $\kappa=20\%$) 43

5-9 Average bed porosity changes as a function of magnetic field intensity and water superficial velocity ($d_p=3.3\text{mm}$, $\kappa=30\%$) 44

5-10 Average bed porosity changes as a function of magnetic field intensity and water superficial velocity ($d_p=2.5\text{mm}$, $\kappa=20\%$) 47

5-11 Plot of $(\varepsilon-\varepsilon_{ms})/(\varepsilon_{if}-\varepsilon_{ms})$ versus $(H-H_{ms})/(-H_{ms})$ 48

5-12 Interaction forces between fluid eddy and induced magnetic forces 49
5-13  Prediction of $H_{ms}$ versus particle Reynolds number for 2 mm particles 52

5-14  Fitting of $H_{ms}$ versus particle Reynolds number for 2 mm particles 53

5-15  Prediction of $H_{ms}$ versus particle Reynolds number for 2.5 mm particles 54

5-16  Fitting of $H_{ms}$ versus particle Reynolds number for 2.5 mm particles 55

5-17  Prediction of $H_{ms}$ versus particle Reynolds number for 3 mm particles 56

5-18  Fitting of $H_{ms}$ versus particle Reynolds number for 3 mm particles 57

5-19  Experimental points $\varepsilon_{ms}$ versus $U_{ms}$ 59

5-20  Experimental points $\varepsilon_{ms}$ versus $U_{ms}$ 60

5-21  $\varepsilon$ versus $U_0$ for 20%-2.5mm, at different $d_p$ 62

5-22  Fitting line for $\varepsilon$ versus $U_0$ for 20%-2.5mm, at different $d_p$ 63

5-23  Particle virtual diameter $d_{vp}$ versus magnetic field strength $H$
a) 2mm particles, b) 2.5mm particles, c) 3mm particles 64
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>MSFB fluidization regimes terminology</td>
</tr>
<tr>
<td>3-1</td>
<td>Particle properties</td>
</tr>
<tr>
<td>3-2</td>
<td>Location of the pressure ports along the column</td>
</tr>
</tbody>
</table>
LIST OF APPENDIX FIGURES

A-1 Magnetic field strength versus the length from the center of the solenoid for a current of 80A 74

B-1 Particles production apparatus 75

C-1 Voltage - intensity (U - I) calibration curve for the magnetic field generator 78

D-1 Calibration curve for the orifice meter 79
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>Constant parameter in (Eq.2-8)</td>
<td>((m/A))</td>
</tr>
<tr>
<td>(A)</td>
<td>Column cross section</td>
<td>((m^2))</td>
</tr>
<tr>
<td>(d_p)</td>
<td>Composite particle diameter</td>
<td>((mm))</td>
</tr>
<tr>
<td>(dvp)</td>
<td>Composite particle virtual diameter</td>
<td>((mm))</td>
</tr>
<tr>
<td>(D)</td>
<td>Column diameter</td>
<td>((mm))</td>
</tr>
<tr>
<td>(f_F)</td>
<td>Friction coefficient</td>
<td>((-))</td>
</tr>
<tr>
<td>(F_b)</td>
<td>Buoyancy force exerted on a particle</td>
<td>((N))</td>
</tr>
<tr>
<td>(F_d)</td>
<td>Drag force exerted on a particle</td>
<td>((N))</td>
</tr>
<tr>
<td>(F_g)</td>
<td>Gravitational force exerted on a particle</td>
<td>((N))</td>
</tr>
<tr>
<td>(F_m)</td>
<td>Magnetic force exerted on a particle</td>
<td>((N))</td>
</tr>
<tr>
<td>(g)</td>
<td>Gravitational acceleration</td>
<td>((m/s^2))</td>
</tr>
<tr>
<td>(g_c)</td>
<td>Conversion factor</td>
<td>((kg \ m/ \ Ns^2))</td>
</tr>
<tr>
<td>(H)</td>
<td>Magnetic field intensity</td>
<td>((A/m))</td>
</tr>
<tr>
<td>(H_{ms})</td>
<td>Magnetic field intensity at the transition between the partially stabilized and the stabilized regimes.</td>
<td>((A/m))</td>
</tr>
<tr>
<td>(H_0)</td>
<td>Characteristic magnetic field strength</td>
<td>((A/m))</td>
</tr>
<tr>
<td>(H_0)</td>
<td>Characteristic magnetic field strength</td>
<td>((A/m))</td>
</tr>
<tr>
<td>(H_{ota})</td>
<td>Characteristic magnetic field strength at terminal velocity</td>
<td>((A/m))</td>
</tr>
<tr>
<td>(i)</td>
<td>Index</td>
<td>((-))</td>
</tr>
<tr>
<td>(I)</td>
<td>Electric current intensity</td>
<td>((A))</td>
</tr>
<tr>
<td>(L)</td>
<td>Bed height</td>
<td>((cm))</td>
</tr>
<tr>
<td>(L_i)</td>
<td>Height of the (i^{th}) pressure port above the distributor</td>
<td>((m))</td>
</tr>
</tbody>
</table>
m Length of the solenoid (cm)
M Magnetization intensity (A/m)
n Richardson-Zaki coefficient in (Eq. 2-2 and 2-3) (Leva, 1959) (/)
N Number of turns in the solenoid (/)
Pᵢ Pressure in the iᵗʰ probe (Pa)
R Electric circuit resistance (W)
R² Regression coefficient (/)
Reᵢ Particle Reynolds number \( \left( = \frac{d_p \rho U_0}{\mu} \right) \) (/)
Reₘₛ Particle Reynolds number at the transition from the partially stabilized to the stabilized regimes (/)
Reₘᵢf Particle Reynolds number at minimum fluidization velocity (/)
s Parameter (in Eq. 2-4) (/)
U Voltage applied to the solenoid (V)
Uₘₛ Water superficial velocity at the transition from the partially stabilized to the stabilized regimes (m/s)
Uₘᵢf Minimum fluidization velocity (m/s)
U₀ Water superficial velocity (m/s)
Uₜ Terminal velocity (m/s)
Vₑ Void function (in Eq. 2-8) (Jovanovic et al., 1993) (/)
W Buoyant weight of particles in the bed (kg)
**NOTATION (CONTINUED)**

**Greek symbols**

\( \alpha \)  
Linear coefficient in the expression of \( \chi \) as a function of \( H \) in (Eq. 2-10)  
\((\text{m/A})\)

\( \beta \)  
Constant coefficient in the expression of \( \chi \) as a function of \( H \) in (Eq. 2-10)  
\((\text{m/A})\)

\( \delta \)  
Parameter in (Eq. 2-6)  
\((/\))

\( \delta_d \)  
Ferrite particle diameter  
\((\text{m})\)

\( \xi \)  
Parameter in (Eq. 2-7)  
\((/\))

\( \Delta P \)  
Pressure drop  
\((\text{Pa})\)

\( \Delta P_{\text{bed}} \)  
Pressure drop across the bed  
\((\text{Pa})\)

\( \Delta P_i \)  
Pressure drop across the portion of the bed between the distributor and the \( i \)th pressure port level  
\((\text{Pa})\)

\( \varepsilon \)  
Bed porosity  
\((/\))

\( \varepsilon_{\text{avg.}} \)  
Average bed porosity  
\((/\))

\( \varepsilon_{\text{calc.}} \)  
Calculated average bed porosity from Richardson-Zaki equation  
\((/\))

\( \varepsilon_{\text{exp.}} \)  
Experimental average bed porosity  
\((/\))

\( \varepsilon_{\text{ff}} \)  
Average bed porosity for \( H=0 \)  
\((/\))

\( \varepsilon_{\text{mf}} \)  
Bed porosity at onset of fluidization  
\((/\))

\( \varepsilon_{\text{ms}} \)  
Average bed porosity at the transition between the partially stabilized and the stabilized regimes  
\((/\))
\[ \varepsilon_m \quad \text{Average bed porosity in the stabilized regime in (Eq. 2-4) (Kwauk et al., 1992)} \]

\[ \varepsilon_{mt} \quad \text{Average bed porosity at the stabilized regime and at terminal velocity} \]

\[ \varepsilon_p \quad \text{Bed porosity in the random motion regime in (Eq. 2-4) (Kwauk et al. 1992)} \]

\[ \varepsilon_{pb} \quad \text{Bed porosity in the packed bed regime} \]

\[ \Phi_s \quad \text{Particle shape factor} \]

\[ \mu \quad \text{Fluid viscosity} \]

\[ \rho \quad \text{Fluid density} \]

\[ \rho_p \quad \text{Particle density} \]

\[ \chi \quad \text{Particle magnetic susceptibility} \]

**Subscripts**

- \( ff \) Free fluidization
- \( i \) Pressure port number
- \( M \) Magnetically condensed regime
- \( ms \) Transition between partially stabilized and stabilized regimes
- \( mf \) Minimum fluidization
- \( p \) Particle

**Abbreviation**

\( \kappa \quad \text{Particle ferrite content by weight} \)
Magnetically stabilized fluidized beds, MSFBs, are fluidized beds of magnetizable particles under the influence of an external magnetic field. The magnetic field is changing the structure of the bed. Hence it creates changes in operating characteristics of the fluidized bed. Fluidized particles align themselves along the magnetic field lines and therefore the fluid-solid interaction is changed. MSFB offers the same low pressure drop as an ordinary fluidized bed allows for the transport of solids through the system, and has an excellent contacting efficiency. The increased contacting efficiency between particles and fluid is the basis for possible improvement of the performance of conventional beds.

Pioneering studies in this area were done by Filippov in 1959. Since then, MSFBs have been extensively researched; such as the elimination of bubbles in gas solid fluidization (Rosensweig, 1979), a magnetic valve for solids (Jaraiz et al., 1984), a magnetic elevator for particles (Wallace et al., 1991) and, bubble properties in a gas solid MSFB (Jovanovic et al., 1996). A good review of experimental research and applications of MSFBs may be found in the articles from Siegell (1989) and Liu et al. (1991).

The study by Filippov (1959) showed that a magnetic field, when applied to a liquid-solid fluidized bed, reduces the bed height and decreases the porosity, although the pressure drop across the bed remains constant. Recently, in the studies by Kwauk (1992) and Honorez (1994), models has been developed to represent and predict the average bed porosity for given particles, magnetic field
strength, and fluid velocity. However, these experimental studies were limited to very particular particles and materials. The goal of this study is to investigate particles with different magnetic susceptibilities so that the proposed equations can be tested over a wider range. In this work, the dynamic structure of liquid-solid MSFBs is studied. Experimental data relate the bed porosity and magnetic property of the particle, and they are used to find an equation predicting the bed porosity for given operating conditions.

Chapter 2 is a review of the fundamental background of MSFBs. Chapters 3 and 4 deal with instrumentation, experimental procedures, and data conversion. Chapter 5 presents the experimental results and attempts to integrate our experimental findings into a useful operating model.
CHAPTER 2
THEORETICAL BACKGROUND

2.1- Magnetically Stabilized Fluidized Bed (MSFB)

One of the fundamental characteristics of MSFB noticed and described by many authors - Kirko and Filippov (1960), Siegel (1987), Kwauk (1992), and Honorez (1994) - is the existence of fluidization regimes that are not encountered in ordinary fluidized beds. Figure 2-1 provides a regime map, or phase diagram which summarizes these observations. Investigators identified four different regimes and used different terminology to describe them. Table 2-1 summarizes some of the terms used for liquid-solid MSFBs. Using established terminology, the following regimes are identified: the packed bed regime, the stabilized regime, the partially stabilized regime, and the random motion regime.

**Packed bed regime** The magnetic field has no influence on the packed bed regime. The bed of particles is immobile, and particles are not fluidized.

**Partially stabilized regime** In the partially stabilized regime, particles form doublets, triplets, and other short chain structures aligned with the magnetic field lines. The bed appears to be quiescent and has a moderate fluidity. With the increase of the magnetic field strength, the bed fluidity decreases and particle chains grow in length and may interact laterally to form intermeshed structures.

**Stabilized regime** In the stabilized regime, the magnetic field is strong enough to completely immobilize particles. Particles form extensive chains in a spaghetti-like fashion. The particles are then no longer fluidized.

**Random motion regime** In the random motion regime, obtained within the range of very low magnetic field strengths, individual particles behave almost
Figure 2-1: Qualitative phase diagram for MSFBs
Table 2-1: MSFB fluidization regimes terminology

<table>
<thead>
<tr>
<th></th>
<th>Packed bed</th>
<th>Pseudopolymerized state</th>
<th>Particle motion regime</th>
<th>Extensive particle mixing regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kirko and Filippov</td>
<td>Packed bed</td>
<td>Pseudopolymerized state</td>
<td>Particle motion regime</td>
<td>Extensive particle mixing regime</td>
</tr>
<tr>
<td>-1960</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Siegell</td>
<td>Unfluidized bed</td>
<td>Frozen bed or Stabilized regime</td>
<td>Roll-cell regime</td>
<td>Random motion regime</td>
</tr>
<tr>
<td>-1987</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Kwauk et al.</td>
<td>Fixed bed</td>
<td>Magnetic condensation regime</td>
<td>Chain regime</td>
<td>Particulate regime</td>
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<td>-1992</td>
<td></td>
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</tr>
<tr>
<td>Jovanovic et al.</td>
<td>Packed bed</td>
<td>Stabilized regime</td>
<td>Partially stabilized regime</td>
<td>Free fluidization state</td>
</tr>
<tr>
<td>-1993</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Honorez</td>
<td>Packed bed</td>
<td>Stabilized regime</td>
<td>Partially stabilized regime</td>
<td>Random motion regime</td>
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<tr>
<td>-1994</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>This study</td>
<td>Packed bed</td>
<td>Stabilized regime</td>
<td>Partially stabilized regime</td>
<td>Random motion regime</td>
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exactly the same as in an ordinary fluidized bed. Particles appear not to be restricted in their motion. The bed is characterized by a random and unimpeded motion of solids.

Thus, the magnetic field can change the structure of the bed from a random motion of particles at low magnetic field strength to a more ordered structure of bed particles at high magnetic field strength. Consequently, fluid-solid contacting is changed.

Siegell (1989) and Liu et al. (1991) presented an excellent review of fundamentals and practical developments related to MSFBs. They summarized more than 30 years of research work in this field and provide an extensive bibliography. Even though there are no complete studies on liquid-solid MSFBs, the earliest work was done by Kirko and Filipov (1960). They studied a liquid-solid system under the influence of an alternating magnetic field colinearly oriented to the liquid flow. They are the first to report on the effect of the magnetic field on bed expansion.

Siegell (1987) demonstrated the effects of the magnetic field and liquid velocity on the bed height for composite particles. The bed height was found not to be a function of the magnetic field strength in the stabilized regime, but to increase steadily only with increasing liquid velocity.

Honorez (1994) demonstrated that for a given magnetic field strength, the average bed porosity increases when the velocity is increased, and that for a given velocity, the average bed porosity decreases when the magnetic field strength is increased.

Kwauk (1992) observed that under the influence of a weak magnetic field, doublets and triplets of particles were formed, mostly oriented in the direction of
the flow. An increase in magnetic field strength increases the lengths of the particle chains and decreases the bed porosity.

From all of these studies one can firmly conclude that the magnetic stabilization of a liquid-solid fluidized bed allows for an enhancement of the liquid-solids contacting. The presence or the absence of particle structures and the degree of bed uniformity is important in determining the applicability of these liquid-solid contactors as chemical reactors or contactors for physical processes.

2.2- Pressure drop through the bed and minimum fluidization velocity

In an ordinary fluidized bed, three types of forces are acting on particles: the gravitational force $F_g$, the drag force $F_d$, and the buoyancy force $F_b$ (Figure 2-2). As the flowrate of fluid is increased, starting from a packed bed, particles move apart and start vibrating and moving within a restricted area. A point is reached when all particles are just suspended by the upward flow of fluid. At that point the drag force on particles counterbalances the buoyant weight of particles. The bed is referred to as a fluidized bed and the velocity at this state is termed the minimum fluidization velocity, $U_{mf}$. A balance of forces gives:

$$ F_d = F_g - F_b = \frac{\pi d^3 p}{6} (\rho_p - \rho) g $$  \hspace{1cm} (Eq. 2-1)

and,

$$ F_d = \frac{1}{2} f_F \rho U^2 $$ \hspace{1cm} (Eq. 2-2)

Further increases in the fluid velocity cannot change (increase) the drag force since the pressure drop is ample enough to carry the weight of particles and hence stays the same.
Filippov (1960) and Siegell (1987) reported that the pressure drop in a magnetic stabilized fluidized bed was equal ($\Delta P = W/A$) to the buoyant weight of the bed, just as in absence of a magnetic field. Also they noticed a decrease of the bed height due to the magnetic field. They believe that the constant value of the pressure drop was due to a more structured (ordered) bed in which channels of lower resistance are formed, permitting the fluid to flow at a higher velocities (still same flow rate) (Figure 2-3).

By using a solenoid shorter than the bed height, Ivanov and Grozev (1970), found that $U_{mf}$ increases with increasing magnetic field. Therefore, they suggested that the effect of the field could be seen as an additional increase of
the weight of particles, thus the increase of the weight of the bed. These findings are obviously in contradiction to previous work by Filippov (1960), Rosensweig (1979), and Siegell (1987) and to the most recent studies by Kwauk (1992) and Honorez (1994). Rosensweig (1979b) suggested that in these early investigations, transition to bubbling is observed, which probably caused the change of the regime of fluidization (from particulate to bubbling) and consequently the change in bed porosity. Another probable reason is suggested by contribution of Liu et al. (1991), in which the increase in $U_{mf}$ appears to be due to the use of a non-uniform magnetic field. Indeed, the non-uniformity of the magnetic field will cause $U_{mf}$ and the pressure drop to increase with increasing magnetic field strength because, an additional force, the magnetic force is acting on particles.

Bologa and Syutkin (1977) recorded a decrease in the bed pressure drop as magnetic field strength is increased. They concluded that this was due to an ever increasing order of the structure of the MSFB. However they failed to explain this phenomenon, from the standpoint of the first principles, i.e., if particles are fluidized, pressure drop must be proportional to the buoyant weight of particles.

Honorez (1994) reported that at very high magnetic field strength the bed porosity reaches a constant minimum value and is unaffected by further increase of the magnetic field strength (Figure 2-4). This experimental observation obviously indicates frozen-packed bed structure of the bed. When these data are compared with pressure drop measurements it becomes clear that at least some of the particles are unfluidized (chains of particles are supported by the distributor plate), and thus lower the pressure drop.

Rosensweig (1979) reported a constant pressure drop across a MSFB at different magnetic field strengths (Figure 2-5). He also noted that the slope of
Figure 2-4: Average bed porosity changes as a function of magnetic field strength for constant water superficial velocities for 1.8 mm diameter ferromagnetic particles from Honorez (1994)
C1018 Steel Spheres

dp = 177-250 [μm]

H = 40 [A/m]

Figure 2-5: Experimental measurement of the minimum fluidization velocity from Rosensweig (1979)
the initial part of the fluidization curve is independent of the uniform field strength and it follows the form of Ergun's equation:

\[
\frac{\Delta P_{\text{bed}}}{L} \cdot g_\varepsilon = 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu U_0}{(\phi_s d_p)^2} + 175 \frac{1-\varepsilon}{\varepsilon^3} \frac{\rho U_0^2}{(\phi_s d_p)} \tag{Eq. 2-3}
\]

Consequently, Rosensweig (1979) concluded that \( U_{mf} \) is independent of the strength of a uniform magnetic field. This confirms a long standing thesis, offered first by Rosensweig and then supported by many other researchers that there are no net interaction forces between particles in a uniform magnetic field.

However, Penchev and Hristov (1990) found that the magnetic field is changing the bed structure due to the interaction forces between particles. The induced magnetic interparticle forces are of cohesive nature and become of utmost importance in MSFB system.

Figure 2-3: Particle arrangement in MSFB as a function of the magnetic field strength; a) Low magnetic field - random distribution of particles, b) High magnetic field - particles are associated in chains along the magnetic field lines and direction of fluid flow
2.3- Porosity in a MSFB

A porosity of any fluidized bed is defined as:

\[
\varepsilon = \frac{\text{Volume of the bed} - \text{Volume of particles}}{\text{Volume of the bed}} \quad \text{(Eq. 2-4)}
\]

Bakker and Heertjes (1958, 1960) defined three possible zones in a fluidized bed based on different bed porosities as shown in Figures 2-6 and 2-7. Zone 1 is adjacent to the distributor plate; its length depends on the distributor plate characteristics. The velocity of the water coming out of the distributor plate orifices is very high. Water flows in small jets for some distance above the distributor. Jets exchange momentum with surrounding fluid and particles. These jets do not allow particles to stay anywhere close to the distributor holes and hence cause an increase of the porosity in Zone 1. Zone 2 is a zone of constant porosity since the jets are no longer influencing the particles. Particles readily exchange momentum with surrounding particles. Zone 3 has a larger porosity. Particles at the top of the bed cannot exchange their momentum with surrounding particles, and hence occasionally penetrate higher in the bed. Figure 2-6 is showing the three porosity zones.

Shumkov and Ivanov (1975, 1977) recorded that at a fixed velocity of fluid, the length of the constant porosity, zone 2, increases at the expense of zone 3 when the magnetic field strength is increased.

A change in the average bed porosity for different fluidization regimes in MSFB was first thoroughly described by Kwauk et al. (1992). They found the following:

1- magnetic field does not affect appreciably the bed porosity in the random motion regime,
Figure 2-6: Porosity zones in a fluidized bed
\( \kappa = 30\% \)
\( d_p = 3.3 \text{ [mm]} \)
\( U_0 = 128 \text{ [mm/s]} \)
\( U_{mt} = 24.1 \text{ [mm/s]} \)

Slope = \( \Delta P_2 / \Delta L_2 \)

Bed height 
\( L = 39 \text{cm} \)

Figure 2-7: Bed height determination for a non uniform bed porosity
2- a constant reduction in bed voidage with increasing field strength is observed in the partially stabilized bed, 
3- the porosity of the bed is constant in the stabilized regime.

Also, Kwauk et al. (1992) are the first to present an equation for the prediction of the average porosity as a function of the magnetic field intensity and other characteristic parameters (\(H_0, s, \varepsilon_M\) and \(\varepsilon_p\)) of the system:

\[
\frac{\varepsilon - \varepsilon_M}{\varepsilon_p - \varepsilon_M} = \exp\left[\left(\frac{H}{H_0}\right)^s\right] 
\]  

(Eq. 2-4)

In the above equation "s" is the slope of the straight line on the \(\ln\left(\frac{\varepsilon_p - \varepsilon_M}{\varepsilon - \varepsilon_M}\right)\) versus \(\ln (H)\) plot, and \(H_0\) is the intercept of the same line. The porosity \(\varepsilon_M\) is defined as the porosity of the bed in the stabilized regime; and \(\varepsilon_p\) is the porosity in the particulate regime (Figure 2-8).

According to Kwauk's study, the \(\varepsilon-H\) curves at constant liquid flow rate show a characteristic S-shape that could be divided into three parts: the particulate regime, the chain regime, and the magnetic condensation regime (see Table 2-1 for terminology).

In a particulate fluidization regime, porosity \(\varepsilon_p\) is related linearly to fluid velocity \(U_0\) by the well-known Richardson-Zaki equation:

\[
\frac{U_0}{U_t} = \varepsilon_p^n \quad \text{and} \quad n = \left(4.45 + 18\frac{d_p}{D}\right)\text{Re}^{-0.1} 
\]  

(Eq. 2-5)
From experimental data it has been found that both the ratio of $H_0$ to its value at the particle terminal velocity $U_t$, and the ratio of $E_M$ to $E_{Mt}$ are related linearly to fluid velocity $U_0$ by the following empirical relations:

$$\frac{H_0}{H_{0t}} = \left(\frac{U_0}{U_t}\right)^\delta \quad \text{(Eq. 2-6)}$$

$$\frac{E_M}{E_{Mt}} = \left(\frac{U_0}{U_t}\right)^\xi \quad \text{(Eq. 2-7)}$$

Jovanovic et al (1993) modified Equation 2-4 to correlate their expansion data obtained in a liquid-solid fluidized bed. They defined the void function $V_\varepsilon$ as follows:

$$V_\varepsilon = \frac{E - E_{ms}}{E_{fs} - E_{ms}} = e^{-aH} \quad \text{(Eq. 2-8)}$$

where $E_{fs}$ is the bed porosity in random motion regime (at $H=0$), and $E_{ms}$ is the bed porosity at the transition between the partially stabilized and the stabilized regime.

Most recently, Honorez (1994) further transformed Equation 2-8 to predict the average porosity for a given set of velocity and magnetic field strength values as:

$$\frac{H_{ms}}{1-\varepsilon} \ln \left(\frac{E - E_{ms}}{E_{fs} - E_{ms}}\right) = -\chi H = -M \quad \text{(Eq. 2-9)}$$

The most attractive feature of the equation proposed by Honorez is that less empirical correlation parameters are needed to predict the bed porosity $\varepsilon$. This
is a qualitative improvement from the result of Kwauk et al. (1992) modeling, where three correlation parameters are needed (s, 8, 4).

Figure 2-3 Honorez(1994) indicates the decrease in porosity while increasing the magnetic field strength at a given fluid velocity. These equations (Equation 2-9) are valid for:

\[ U_0 \geq Umf \quad \text{and} \quad H < Hms \quad \text{(Eq. 2-10)} \]

as long as magnetic saturation of particles is not reached. M is the magnetization and is defined as:

\[ M = \chi H = (\alpha H + \beta)H \quad \text{(Eq. 2-11)} \]

where \( \chi \) is the magnetic susceptibility. For variety of materials \( \chi \) is defined as a linear function of \( H \) (ie: \( \chi = \alpha H + \beta \)).

2.4- Virtual diameter

For a given fluid velocity above the minimum fluidization velocity, particles are suspended by the upward flow of fluid, the drag force exerted on the particles by fluid overcomes the weight of the particles. When the forces acting on particles are balanced (net force is zero), the bed height and consequently bed porosity are maintained constant. However, when a uniform magnetic field is introduced, the bed height typically decreases. A constant reduction in bed height with increasing field strength is observed. Particles, containing of ferromagnetic material, are attracted to each other, resulting in a change of the bed structure. The applied magnetic field, causes and maintains association of few fluidized particles. We propose that these small clusters of particles are seen by the fluid as a single particle having a larger diameter which we defined as ' particle virtual diameter ' (Figure 2-9), \( d_{vp} \).
Figure 2-8: a) Average bed porosity, and b) $\ln \left( \frac{\varepsilon_p - \varepsilon_M}{\varepsilon - \varepsilon_M} \right)$ versus $\ln(H)$  

(Eq. 2-4) plot from Kwauk (1992)
Figure 2-9: The concept of particle virtual diameter; a) random distribution of particles, b) under a magnetic field, particles associate in chains, c) particles associations are "seen" by the fluid as large particles with equivalent virtual particle diameter, d) decrease in bed height due to the increase in particle apparent (virtual) diameter.
Since the fluid flow rate is not changed, the drag force exerted on particle clusters is then not sufficient to support the weight of these virtual particles. Therefore, the height of the bed must decrease to a point at which a new equilibrium of forces is reached. The decrease in bed height reduces the porosity of the bed, and increases the interstitial fluid velocity, which will then increase the drag force to balance the increase in particle size. Further increase in the magnetic field creates larger association of particles (chains) which in turn cause the bed height to decrease. At very high magnetic fields, a point is reached where further increase in the magnetic field will no longer effect the bed height, simply because all particles find themselves in a packed bed situation. Particles do not move and the bed is frozen. Particles are stacked on top of each other in a spaghetti-like structure. This structure offers lower resistance to the flow of fluid since particles do not have to be supported by the fluid.
CHAPTER 3
APPARATUS

A schematic representation of the experimental apparatus used in this study is shown in Figure 3-1. The apparatus consists of several parts:

1 - the fluidization column with particles,
2 - the water supply system,
3 - the pressure measuring system,
4 - the magnetic field generator.

3.1 - Fluidization column with particles

Fluidization column: The column in which the particles are fluidized is made of Plexiglas, allowing visual observation through the wall. It is assembled from two removable parts: a calming section at the bottom, followed by the fluidization column, a 670 mm long cylinder, 52 mm internal diameter, which fits into the calming section. The distributor plate is located inside the column, and it can be easily replaced, repositioned or removed.

The fluid distributor plate is made of perforated Plexiglas, 6 mm thick and 51 mm in diameter. It has two hundred sixty two circular holes 1.2mm in diameter. Seven pressure ports on the column wall are used for pressure measurements. Their locations are reported in Table 3-2.

The bed is operated at room temperature and atmospheric pressure.

The particles: Nine different groups of (composite) particles containing ferromagnetic material are used in this study. Their properties are summarized
Figure 3-1: Experimental apparatus
Table 3-1: Particle properties

<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Mean $d_p$ (mm)</th>
<th>Ferrite Content mass fraction</th>
<th>Ferrite Content volumetric fraction</th>
<th>$\rho_p$ (kg/m$^3$)</th>
<th>$U_{mf,exp}$ (mm/s)</th>
<th>$U_{mf}$ (Eq. 2-2) (mm/s)</th>
<th>$\varepsilon_{pb}$ (/)</th>
<th>$\varepsilon_{mf}$ (/)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.9</td>
<td>10</td>
<td>2.98</td>
<td>1190</td>
<td>5.5</td>
<td>4.1</td>
<td>0.40</td>
<td>0.48</td>
</tr>
<tr>
<td>2</td>
<td>2.0</td>
<td>20</td>
<td>7.55</td>
<td>1510</td>
<td>8.0</td>
<td>10.2</td>
<td>0.40</td>
<td>0.56</td>
</tr>
<tr>
<td>3</td>
<td>2.0</td>
<td>30</td>
<td>13.58</td>
<td>1810</td>
<td>14.7</td>
<td>14.5</td>
<td>0.40</td>
<td>0.50</td>
</tr>
<tr>
<td>4</td>
<td>2.5</td>
<td>10</td>
<td>3.03</td>
<td>1210</td>
<td>9.0</td>
<td>6.9</td>
<td>0.40</td>
<td>0.46</td>
</tr>
<tr>
<td>5</td>
<td>2.5</td>
<td>20</td>
<td>7.40</td>
<td>1480</td>
<td>15.2</td>
<td>12.9</td>
<td>0.40</td>
<td>0.46</td>
</tr>
<tr>
<td>6</td>
<td>2.6</td>
<td>30</td>
<td>13.65</td>
<td>1820</td>
<td>20.0</td>
<td>19.5</td>
<td>0.40</td>
<td>0.51</td>
</tr>
<tr>
<td>7</td>
<td>3.0</td>
<td>10</td>
<td>2.95</td>
<td>1180</td>
<td>9.0</td>
<td>7.8</td>
<td>0.40</td>
<td>0.51</td>
</tr>
<tr>
<td>8</td>
<td>3.1</td>
<td>20</td>
<td>7.65</td>
<td>1530</td>
<td>19.0</td>
<td>17.4</td>
<td>0.40</td>
<td>0.46</td>
</tr>
<tr>
<td>9</td>
<td>3.3</td>
<td>30</td>
<td>13.50</td>
<td>1800</td>
<td>24.1</td>
<td>24.0</td>
<td>0.40</td>
<td>0.51</td>
</tr>
</tbody>
</table>
in Table 3-1. Manufacturing of these composite particles is described in Appendix B. Composite particles are produced using dionized water, sodium alginate (Keltone HV) a product from Kelco (Division of Merck & Co. Inc) and ferrite powder. Ferrite powder was bought from Steward Ferrites (Chattonooga, Tennessee, USA). Ferrite and alginate sodium properties are summarized in Appendix B (Table B-1).

The density of the composite fluidization particle is determined from volumetric and weight measurements in water.

Composite particles contain ferrite powder uniformly dispersed as schematically shown in Figure 3-2.

![Figure 3-2: Ferromagnetic composite particles](image)

Minimum fluidization velocity is experimentally determined from pressure drop measurements at different water velocities. Figure 3-3 shows a typical $\Delta P-U_0$ diagram. Obtained values of the minimum fluidization velocity match reasonably well estimated velocities from Ergun correlation for spherical particles (Equation 2-3.)
3.2 - The water supply system

Water from the city supply network is used. The water flow rate is measured by an orifice meter installed in the supply line below the fluidized bed. Calibration curve is given in the Appendix D. Any desired flow rate of water from 0 to 0.5 l/s can be adjusted by control valve.

3.3 - The pressure measuring system

The pressure measuring system consists of a bank of seven piezometric glass tubes, 4mm in diameter. Each of them is connected to its corresponding pressure port mounted on the column wall. Each pressure port is covered with plastic wire-mesh screen to prevent particles from entering the tubes. The locations of the pressure ports along the fluidization column are given in Table 3-2.

Table 3-2: Location of the pressure ports along the column

<table>
<thead>
<tr>
<th>Pressure port number</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height from the distributor plate (mm)</td>
<td>0</td>
<td>50</td>
<td>100</td>
<td>155</td>
<td>205</td>
<td>255</td>
<td>310</td>
</tr>
</tbody>
</table>

3.4 - The magnetic field generator

The magnetic field is generated by passing direct electric current through a copper coil wound around the fluidization column. The solenoid has a diameter
Figure 3-3: Experimental measurement of the minimum fluidization velocity
diameter of 102 mm. Ninety turns of copper tube are wound around the fluidization column to a length of 480 mm. The copper coil and power supplies are connected in a series as shown in Figure 3-1. Each power supply can provide a voltage between 0 and 5 V. The voltage is controlled at each power supply and monitored by a voltmeter connected to the ends of the solenoid. The total resistance of the electrical circuit (power supplies, solenoid, connecting wires) is 0.0731 Ω. Theoretically this arrangement allows for a delivery of electric current from 0 to 140 A, which can generate a magnetic field strength from 0 to 26,000 A/m. The nominal magnetic field is calculated from the following equation:

\[
H = \frac{IN}{m} \quad \text{(A / m)}
\]

(Eq. 3-1)

where \( m \) is the length of the solenoid, \( I \) the electric current, and \( N \) the number of turns in the solenoid.

A detailed calculation of the field at any point within and outside of the solenoid is calculated from equations presented in Appendix A.

As current is applied to the solenoid, the solenoid has to be continuously cooled. Water flowing inside the copper tube keeps the coil at a reasonable temperature so that resistance of the system can be considered constant. The practical range for the magnetic field intensity is from 0 to 22,000 A/m.

The accuracy of the voltage measurement is 0.05 V, which is equivalent to a magnetic field of 130 A/m. The voltage-current calibration curve of the system is shown in Appendix C. The strength of the magnetic field along the central axis of the solenoid is shown in Appendix A. The bed is positioned in the center of the solenoid so that the maximum variation of the field strength along the bed is less than 2%.
CHAPTER 4
EXPERIMENTAL MEASUREMENTS

The pressure measurements at each of the seven locations along the fluidization column at a given water flow rate and magnetic field intensity are used to obtain data for:

1 - the overall pressure drop across the bed
2 - the bed height needed for porosity calculations

4.1 - The overall pressure drop across the bed

The overall pressure drop across the bed is calculated (as long as the bed height is below the level of the seventh pressure port) by Eq. 4-1:

\[ \Delta P_{\text{bed}} = P_0 - P_7 \]  
(Eq. 4-1)

4.2 - Height of the bed

The pressure drop \( \Delta P \) between the distributor plate port *0* and any pressure port is calculated by:

\[ \Delta P_i = P_0 - P_i \]  
(Eq. 4-2)

The bed height \( L \) is determining by plotting \( \Delta P_{\text{bed}} \) versus the pressure probe location \( L_i \) as shown in Figure 4-1. The pressure drop \( \Delta P \) is decreasing linearly
Figure 4-1: The determination of the bed height (κ=20%w ferrite content)
as \( L \) increases until it becomes zero at the top of the bed. Therefore, the height of the bed is found at \( \Delta P = 0 \).

### 4.3 - Porosity of the bed

Once the bed height is determined for a given water flow rate and magnetic field strength, one can calculate the average bed porosity. Bed porosity can be derived independently from a force balance across the fluidized bed and from a particle material mass balance.

For a uniform average bed porosity \( \varepsilon_{\text{avg}} \), a force balance across the fluidized bed is given by:

\[
\Delta P_{\text{bed}} = \frac{W}{A} = L(\rho_p - \rho)(1 - \varepsilon)g \quad \text{(Eq. 4-3)}
\]

or

\[
\frac{\Delta P_{\text{bed}}}{L} = (\rho_p - \rho)(1 - \varepsilon)g \quad \text{(Eq. 4-4)}
\]

where \( \frac{\Delta P_{\text{bed}}}{L} \) is the slope of the straight line obtained from Figure 4-1.

Hence the bed porosity \( \varepsilon \) is evaluated as:

\[
\varepsilon = 1 - \frac{\Delta P_{\text{bed}}}{(\rho_p - \rho)gL} \quad \text{(Eq. 4-5)}
\]

Bed porosity can also be evaluated using a particle material mass balance:

\[
\left( \text{Buoyant weight of the packed bed} \right) = \left( \text{Buoyant weight of the fluidized bed} \right)
\]
or in symbols,

\[(\rho_p - \rho)gAL_0(1 - \varepsilon_0) = (\rho_p - \rho)gAL(1 - \varepsilon)\]  
(Eq. 4-6)

so,

\[L_0(1 - \varepsilon_0) = L(1 - \varepsilon)\]  
(Eq. 4-7)

which leads to

\[\varepsilon = 1 - \frac{L_0(1 - \varepsilon_0)}{L}\]  
(Eq. 4-8)

where \(L_0\) and \(\varepsilon_0\) are respectively packed bed height and porosity.

Bakker and Heertjes (1958, 1960) characterized three different zones in a fluidized bed based on the distribution of the bed porosity (Figures 2-6 and 2-7). As discussed earlier in section 2-3, zone 1 extends upward from the distributor plate and its length depends on the distributor plate characteristics. Zone 2 is typically a homogenous layer of particles. Zone 3 has a larger porosity. According to Shumkov and Ivanov (1975, 1977) the length of zone 2 expands at the expense of zone 3 with increasing magnetic field.

A similar phenomenon is observed throughout our experiments and confirmed from the diagram of pressure drop \(\Delta P\) versus the distance \(\Delta L_i\) (Figure 4-2). An average bed porosity \(\varepsilon_{avg}\) is evaluated from the following equation:

\[\varepsilon_{avg} = \frac{\Delta L_1}{L}\varepsilon_1 + \frac{\Delta L_2}{L}\varepsilon_2 + \frac{\Delta L_3}{L}\varepsilon_3\]  
(Eq. 4-9)
$\kappa = 30\%$

$\rho_p = 3.3\text{mm}$

$U_o = 12.83 \text{ [cm/s]}$

**Figure 4-2:** Pressure drop in a bed with non uniform porosity distribution
where $\Delta L_1$, $\Delta L_2$ and $\Delta L_3$ are the heights of zone 1, zone 2 and zone 3 of the bed. Figure 4-2 shows clearly the three different fluidization porosity zones.

Porosity $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_3$ are evaluated from the balance of forces in the three fluidization zones which leads to the following equations:

\[
\varepsilon_1 = 1 - \frac{\Delta P_1}{\Delta L_1 (\rho_p - \rho)g} = 1 - \frac{\Delta P_1}{\Delta L_1 (\rho_p - \rho)g} \quad \text{(Eq. 4-10)}
\]

\[
\varepsilon_2 = 1 - \frac{\Delta P_2}{\Delta L_2 (\rho_p - \rho)g} = 1 - \frac{\Delta P_2}{\Delta L_2 (\rho_p - \rho)g} \quad \text{(Eq. 4-11)}
\]

\[
\varepsilon_3 = 1 - \frac{\Delta P_3}{\Delta L_3 (\rho_p - \rho)g} = 1 - \frac{\Delta P_3}{\Delta L_3 (\rho_p - \rho)g} \quad \text{(Eq. 4-12)}
\]

where $\frac{\Delta P_1}{\Delta L_1}$, $\frac{\Delta P_2}{\Delta L_2}$, and $\frac{\Delta P_3}{\Delta L_3}$ are the slopes of the three fitted straight lines shown in Figure 4-2. Then, the average bed porosity $\varepsilon_{avg}$ is calculated with the help of Equation 4-9. The result of this calculation represents a single point on the $\varepsilon$-H graph (Figure 5-1).
The experiments conducted in this study allow us to focus our attention on changes in the average bed porosity as a function of both, water superficial velocity and magnetic field strength.

In this chapter we will develop a model for the prediction of the average bed porosity as a function of fluidization conditions, fluid properties, particle porosity and magnetic field strength.

5.1- Average bed porosity

The average bed porosity is calculated from bed height measurements as discussed in Chapter 4. Figures 5-1 through 5-9 show the bed porosity as a function of the magnetic field strength, and the water superficial velocity for all nine group of particles.

From these figures, we can see that:
- for a given magnetic field strength, the average bed porosity increases when the superficial fluid velocity is increased,
- for a given superficial fluid velocity, the average bed porosity decreases when the magnetic field strength is increased,
- at high magnetic fields (\(H \geq H_{ms}\)), particles are immobile (i.e. the bed is frozen). The average bed porosity is then constant.
- the average bed porosity reaches a minimum at a particular field strength \(H_{ms}\). For magnetic field strengths beyond \(H_{ms}\) (i.e. \(H > H_{ms}\)), the bed porosity of the frozen bed increases.
Figure 5-1: Average bed porosity changes as a function of magnetic field intensity and water superficial velocity

\( (d_p = 1.9 \text{ mm}, \kappa = 10\%) \)
Figure 5-2: Average bed porosity changes as a function of magnetic field intensity and water superficial velocity 
\((d_p = 2 \text{mm}, \kappa = 20\%\))
Figure 5-3: Average bed porosity changes as a function of magnetic field intensity and water superficial velocity
($d_p = 2\text{mm}, \kappa = 30\%$)
Figure 5-4: Average bed porosity changes as a function of magnetic field intensity and water superficial velocity
\((d_p = 2.5\, \text{mm}, \kappa = 10\%)\)
Figure 5-5: Average bed porosity changes as a function of magnetic field intensity and water superficial velocity 
\( d_p = 2.5 \text{ mm}, \kappa = 20\% \)
Figure 5-6: Average bed porosity changes as a function of magnetic field intensity and water superficial velocity
(dp = 2.6 [mm], \( \kappa = 30\% \))
Figure 5-7: Average bed porosity changes as a function of magnetic field intensity and water superficial velocity 
\( d_p = 3 \text{mm}, \kappa = 10\% \)
Figure 5-8: Average bed porosity changes as a function of magnetic field intensity and water superficial velocity 
($d_p = 3.1\, \text{mm}, \kappa = 20\%$)
Figure 5-9: Average bed porosity changes as a function of magnetic field intensity and water superficial velocity

(dp = 3.3 mm, k = 30%)
To gain better understanding of this phenomenon, one should notice the change of the overall pressure drop, $\Delta P_{\text{bed}}$, for the bed in the stabilized regime (frozen state). In the stabilized regime, particles are arranged in spaghetti like fashion, and most likely are sitting on the distributor plate. These spaghettis form channels, which offer lower resistance to fluid flow, thus lowering the overall pressure drop $\Delta P_{\text{bed}}$. This behavior of the frozen bed was observed in previous studies by Honorez (1994) and Jovanovic, (1993).

Several attempts were previously made to find an expression which can successfully predict the bed porosity in MSFB by encompassing all relevant variables into one consistent mathematical model/correlation. We already mentioned the work of Kwauk (1992),

$$\frac{\varepsilon - \varepsilon_M}{\varepsilon_p - \varepsilon_M} = \exp\left[-\frac{H}{H_0}\right]^{S} \tag{Eq. 2-4}$$

Jovanovic et al. (1993),

$$V_{\varepsilon} = \frac{\varepsilon - \varepsilon_{\text{ms}}}{\varepsilon_f - \varepsilon_{\text{ms}}} = e^{-aH} \tag{Eq. 2-8}$$

and Honorez and Jovanovic (1994),

$$\frac{H_{\text{ms}}}{1 - \varepsilon} \ln\left(\frac{\varepsilon - \varepsilon_{\text{ms}}}{\varepsilon_f - \varepsilon_{\text{ms}}}\right) = -M \tag{Eq. 2-9}$$

Following the work by Kwauk (1992), Jovanovic (1993) and Honorez (1994), we now propose a simple set of equations to predict the average bed porosity for any set of values of the velocity and the magnetic field.
\[
\frac{\varepsilon - \varepsilon_{ms}}{\varepsilon_{ff} - \varepsilon_{ms}} = \frac{H - H_{ms}}{H_{ff} - H_{ms}} = \frac{H - H_{ms}}{-H_{ms}}
\]  
(Eq. 5-1)

This equation is valid for \( U_0 > U_{mf} \) and \( H < H_{ms} \) as long as magnetic saturation of the particles is not reached.

Three parameters appear in Equation 5-1, \( \varepsilon_{ff}, \varepsilon_{ms}, \) and \( H_{ms} \) (Figure 5-10). \( \varepsilon_{ff} \) is the porosity of the bed at a given velocity and \( H = 0 \). It can be easily calculated from the Richardson-Zaki equation (Leva, 1959).

\[
\frac{U_0}{U_t} = \varepsilon_{ff}^n \quad \text{which leads to} \quad \varepsilon_{ff} = \left( \frac{U_0}{U_t} \right)^{\frac{1}{n}}
\]  
(Eq. 5-2)

where \( n \) is given by

\[
n = \left( 4.45 + 18 \frac{dp}{D} \right) \text{Re}^{-0.1} \quad \text{for} \quad 200 < \text{Re}_p < 500, \quad \text{and} \n
n = 4.45 \times \text{Re}_p \quad \text{for} \quad 0 < \text{Re}_p < 200
\]

The porosity \( \varepsilon_{ff} \) is a function of the fluid velocity, the particle Reynolds number, and the terminal velocity of particles.

The \( \varepsilon_{ms} \) is the average bed porosity at the transition between the partially stabilized and the stabilized regimes. \( H_{ms} \) is the corresponding magnetic field intensity at the transition between the partially stabilized and the stabilized regimes.

Figure 5-11 shows how closely Equation 5-1 represents our experimental data. In an effort to find correlation between \( H_{ms} \) and \( \varepsilon_{ms} \), the association of particles in chains needs to be looked at. The stability of any particle-particle association (two, three, and more particles together leading to stabilized regime) depends on a delicate balance of forces acting on these particles.
Figure 5-10: Average bed porosity changes as a function of magnetic field intensity and water superficial velocity 

(d_p= 2.5 mm, \( \kappa=20\% \))
Figure 5-11: Plot of $(\varepsilon_{\varepsilon_{\text{ms}}}/(\varepsilon_{\text{ms}}) - \varepsilon_{\text{ms}})$ versus $(H-H_{\text{ms}})/(-H_{\text{ms}})$
Two types of forces are predominantly responsible for the existence and stability of these particulate structures

a) fluid to particle dispersion forces;
b) particle to particle attraction forces.

Let us consider two particles of the same size, density, and ferrite content, which just formed an aggregate at a given field strength \( H_{ms} \) and fluid velocity \( U_{ms} \).

*Figure 5-12: Interaction forces between fluid eddy and induced magnetic forces*

Dispersion forces acting on these particle structures are generated from the momentum exchange between fluid and particles. These forces may break particle association. Momentum is exchanged through laminar shear stress, (friction of fluid on the surface of the particle) and through an occasional collision
between fluid eddy and particle. Both of these mechanisms of momentum exchange result in forces that can separate/disperse particles. We believe that particle Reynolds number can capture adequately the influence of these forces on the particulate structure.

\[ \text{Rep} = \frac{\rho U \sigma_d p}{\varepsilon_m \mu} \]  

(Eq. 5-3)

The particle to particle attraction force is obviously dependent on the magnetization of the particles. The external field \( H \) magnetizes ferromagnetic material contained inside the fluidization particles (beads) turning them into small magnets that attract each other. As evident from many experimental observations these attraction forces may grow very strong, to finally immobilize and defluidize all particles. The strength of the attraction forces depends on four obvious parameters/variables: magnetic properties of the ferromagnetic powder contained inside the fluidization particles, the volume fraction of the ferromagnetic powder inside the beads, the strength of the external magnetic field, and the size/shape of the particles. We believe that induction field, \( B \), captures the influence of all of the above mentioned factors.

\[ B = \mu_0 H + \mu_0 M \]  

(Eq. 5-4)

Still, there is one important consideration when it comes to the estimation of the influence of the volumetric fraction of the ferromagnetic powder contained inside the beads. Ferromagnetic material is not homogeneously dissolved or spread inside the beads. It is rather homogeneously dispersed as discrete powder particles \( \delta_p = 3-6 [\mu m] \). It is now not hard to imagine induction fields associated with each of these ferromagnetic powder particles. The overall induction field of one fluidization bead will depend on the strength and the average distance between induction fields of the individual ferromagnetic powder particles. It is
obvious that if ferromagnetic particles are closer to each other their overall induction will be stronger.

The induction field around a ferromagnetic powder particle is inversely proportional to the square of the distance from the particles. At the same time, the average distance between powder particles is proportional to the third root of their volume fraction. Considering the geometry of the system, it is difficult to determine how attraction force between two bead particles depends on the induction field. Finding an exact relationship would just be an academic exercise since the true relationship between powder content of the bead and the strength of the attracting force depends on very many other parameters, which are beyond the control of the experiment. Nevertheless one can expect that the strength of the attracting force will depend strongly on the volume fraction of the ferromagnetic powder.

This is confirmed from the Figures (5-13, 5-14, and 5-15) showing a plot of $H_{ms}$ versus particle Reynolds number.

To make use of the Equation 5-1, a correlation between $\varepsilon_{ms}$ and $H_{ms}$ must be found. One should remember that $H_{ms}$ is the magnetic field needed to reach the transition between the partially stabilized regime and the stabilized regime, and $\varepsilon_{ms}$ the average bed porosity at the transition between the partially stabilized regime and the stabilized regime. We propose the following form for these correlations.

$$H_{ms} = a(V\%)^\nu (Re_{ms} - Re_{mf}) + H_{ms0} \quad \text{(Eq. 5-5)}$$

For 2mm particles,

$$H_{ms} = 0.97(V\%)^{-1.46} (Re_{ms} - Re_{mf}) + 500 \quad \text{(Eq. 5-6)}$$
Figure 5-13: Prediction of $H_{ms}$ versus particle Reynolds number for 2 mm particles
Figure 5-14: Fitting of $H_{ms}$ versus particle Reynolds number for 2 mm particles
Figure 5-15: Prediction of $H_{ms}$ versus particle Reynolds number for 2.5 mm particles
Figure 5-16: Fitting of $H_m$ versus particle Reynolds number for 2.5 mm particles
Figure 5-17: Prediction of $H_{ms}$ versus particle Reynolds number for 3 mm particles
Figure 5-18: Fitting of $H_{ms}$ versus particle Reynolds number for 3 mm particles
For 2.5mm particles,

\[ H_{ms} = 0.72(V\%)^{-1.20}(Re_{ms} - Re_{mf}) + 1000 \]  \hspace{1cm} (Eq. 5-7)

For 3mm particles

\[ H_{ms} = 0.13(V\%)^{-1.41}(Re_{ms} - Re_{mf}) + 1500 \]  \hspace{1cm} (Eq. 5-8)

The intercept \( H_{ms0} \) should represent a corresponding minimum magnetic field strength needed at minimum fluidization to stabilize the bed.

If one wants to use the fit for all of them, the correlation is then:

\[ H_{ms} = 0.607(V\%)^{-1.36}(Re_{ms} - Re_{mf}) + 1000 \]  \hspace{1cm} (Eq. 5-9)

In addition to above correlations, an experimental correlation between \( \varepsilon_{ms} \) and \( H_{ms} \) is found.

\[ \varepsilon_{ms} = a \times H_{ms} + b \]  \hspace{1cm} (Eq. 5-10)

This correlation is valid at \( U_0=U_{ms} \) and "a" and "b" empirical parameters found by fitting experimental data to a linear equation \( y = ax + b \). The intercept \( b \) should represent a corresponding porosity of minimum fluidization (Figure 5-19, and 5-20):

1 - for \( \kappa=10\% \)

\[ \varepsilon_{ms} = 0.0011 \times H_{ms} + 0.4842 \]  \hspace{1cm} (Eq. 5-11)
Figure 5-19: Experimental points of $\varepsilon_{ms}$ versus $H_{ms}$
Figure 5-20: Experimental points of $\varepsilon_{ms}$ versus $H_{ms}$
2- for $\kappa = 20\%$

$$\varepsilon_{ms} = 0.0138 \times H_{ms} + 0.5083 \quad \text{(Eq. 5-12)}$$

3- for $\kappa = 30\%$

$$\varepsilon_{ms} = 0.0211 \times H_{ms} + 0.5052 \quad \text{(Eq. 5-13)}$$

**5.2- Particle virtual diameter**

In an ordinary liquid-solid fluidized bed (in the absence of the magnetic field), average bed porosity is evaluated from the Richardson-Zaki equation (Leva, 1959). Bed porosity is a function of the fluid velocity, the particles Reynolds number and the particle terminal velocity (Equation 5-2).

Figure 5-17 shows the $\varepsilon-U_0$ relationship obtained from our experimental data. In the same Figure, experimental data for the average bed porosity at different field strengths are also included. A solid line forms the Richardson-Zaki equation calculated for $d_p=3\text{mm}$ and $H=0$. One would like to know what should be the virtual diameter of particles needed to match the values of the bed average porosity experimentally obtained at different magnetic fields, to the bed porosity with the values of Richardson-Zaki equation at $H=0$.

By adopting Richardson-Zaki and using an optimization routine, virtual particle diameter is found by minimizing the difference between calculated porosity and the experimental values obtained $(\sum(\varepsilon_{calc.}-\varepsilon_{exp.})^2)$ at different magnetic field strength.

Values of the virtual diameter are then plotted versus the magnetic field strength. As expected the diameter of these particles is dependent on the fraction of ferrite material inside the particles. As the amount of ferrite is increasing, the virtual diameter of the particle is increasing at a given magnetic field (Figure 5-18).
Figure 5-21: $\varepsilon$ versus $U_0$ for 20%-2.5mm, at different $dp$
R-Z, dp=2 mm, H=0 A/m
R-Z, dp=2.5 mm, H=0 A/m
R-Z, dp=3.5 mm, H=0 A/m
Exp., dp=2.5 mm, 20%, H=6 kA/m
Exp., dp=2.5 mm, 20%, H=9 kA/m

Figure 5-22: Fitting line for $\epsilon$ versus $U_0$ for 20%-2.5 mm, at different dp
Figure 5-23: Particle virtual diameter dvp versus magnetic field strength H; a) 2mm particles, b) 2.5mm particles, c) 3mm particles
Values of the virtual diameter are then plotted versus the magnetic field strength. As expected the diameter of these particles is dependent on the fraction of ferrite material inside the particles. As the amount of ferrite is increasing, the virtual diameter of the particle is increasing at a given magnetic field (Figure 5-18).

The following correlation for $d_{vp}$ is obtained:

$$d_{vp} = d_p + a_1H + a_2H^2 \quad \text{(Eq. 5-14)}$$
CHAPTER 6
CONCLUSION AND RECOMMENDATIONS

This study was conducted to produce original experimental data and confirm that a magnetic field can influence liquid fluidization of magnetic solids.

Distribution of pressure drop along the bed height proves that the bed porosity varies from the bottom to the top of the bed. For high fluid velocities, three zones of porosities are detected. The applied field tends to make the bed uniform in porosity.

In this study an equation was found to predict the average bed porosity for given particles, velocity, and magnetic field strength (Equation 5-1):

\[
\frac{\varepsilon - \varepsilon_{ms}}{\varepsilon_{ff} - \varepsilon_{ms}} = \frac{H_{ms} - H}{H_{ff} - H_{ms}}
\]  
(Eq. 5-1)

An experimental correlation between \(H_{ms}\) and the particle Reynolds number is given, where \(H_{ms}\) is the magnetic field needed to reach the transition between the partially stabilized regime and the stabilized regime. Also, an experimental correlation between \(\varepsilon_{ms}\) and \(H_{ms}\) is given.

The concept of the virtual particle diameter is confirmed experimentally (Figure 5-19). As expected the diameter of the particles is dependent on the fraction of ferrite material inside the particles. As the amount of ferrite is increasing, the virtual diameter of the particle is increasing for a given magnetic field. For a given volume fraction of ferrite, the diameter of the particle is increasing as the magnetic field strength is increasing.
For future study, we recommend extension of this work on mixtures of ferromagnetic and nonmagnetic particle with different magnetization susceptibilities so that proposed equations can be tested more rigorously.

More work is needed to establish a relationship between the distributor plate characteristics and its influence on bed structure. One should determine the effect of a distributor type (i.e. porous plate, perforated plate,...) on $\varepsilon_{ms}$-$H_{ms}$ correlation. This correlation is most likely sensitive to distributor design.

The concept of the virtual particle diameter should be tested with respect to other operations in the MSFB. For example, enhanced mass transfer coefficient in MSFB may be connected with the virtual particle diameter concept. The enhancement of mass and heat transfer rates in fluidized beds is what we are mainly interested in. The knowledge of how to design MSFBs and how to predict porosity, mass and heat transfer between fluid and particles will allow us to capitalize on the advantages of MSFBs over conventional fluidized beds.


Rosensweig R. E., Magnetic stabilization of the state of uniform fluidization., *Ind. Chem. Sci.*, Vol. 18 No. 3 (1979b) 260


Siegell J. H., Liquid-fluidized magnetically stabilized beds *Powder Technol.*, 52 (1987) 139


APPENDICES
If $L$ is the length of the solenoid, $D$ the diameter, $i$ the current in the windings and $x$ the distance from the center of the solenoid, then the magnetic field strength on the axis of a thin solenoid of finite length at $x$ is given by:

$$H = \left( \frac{Ni}{L} \right) \left[ \frac{(L + 2x)}{\sqrt{2[D^2 + (L + 2x)^2]}} + \frac{(L - 2x)}{\sqrt{2[D^2 + (L - 2x)^2]}} \right]$$  \hspace{1cm} (Eq. A-1)

Figure A-1 shows the magnetic field strength versus the distance from the center of the solenoid for a current of 80A. Figure A-1 shows that MSFB is operated in the region of predominantly, (within 2% difference) uniform magnetic field.
Figure A-1: Magnetic field strength versus the length from the center of the solenoid for a current of 80A
APPENDIX B
PARTICLES PRODUCTION

The particles used in this study are composite ferromagnetic particles which are made of mixture of alginate and ferrite powder. The particles production schematic diagram is shown in Figure B-1.

Air to shear off the solution

Air to push the solution

Vessel

Sodium alginate solution + Ferrite

Particle generator

Composite particles

Calcium chloride solution

Figure B-1: Particles production apparatus

Preparation of the ferromagnetic sodium alginate solution:

The preparation of the ferromagnetic sodium alginate is given by the following instructions:

1- Weigh a 393 [g] amount of distilled water and place the beaker under the mixer,
2- Weigh a 7 [g] amount of sodium alginate powder that will constitute 1.75% of the total weight of water + alginate,
3- Start mixing the water and add the alginate powder to the water in a small increments away from the mixer until all alginate powder is added to the water,
4- Mix the solution for about 20 minutes. During this time, the solution high viscosity could force the mixer to stop. Consequently, the solution has to be continuously checked over the mixing period,
5- Weigh the amount of ferrite powder that will constitute 10, 20% or 30% of the total weight of alginate solution,
6- Add the ferrite powder to the alginate solution in a small increments while stirring the mixture,
7- Repeat step 6 until all ferrite powder is added and a uniform ferromagnetic alginate solution is obtained.

_Mechanism of alginate droplet formation:

The mechanism of alginate droplet formation and experimental parameters for their production depend on incoming air flux rate in the particle generator, the pressure in the vessel, alginate solution viscosity and surface tension.

The particle size is adjusted by regulating the pressure drop and the air flow, which is used to shear the particles off the needle. Increasing the incoming flux rate of air inlet in the particle generator, we can produce smaller particles. Decreasing the pressure in the vessel, we can generate smaller particles.

After the vessel is pressurized, the liquid meniscus at the tip needle is distorted from a spherical shape into an inverted cone-like shape. Hence, alginate solution flows into this cone at an increasing rate causing formation of a neck-like filament. Filament breaks away, producing droplets, the meniscus relaxed back to a spherical shape until flow of the alginate caused the process to start again.

The particles obtained in the particle generator are roughly of the same size if parameters (pressure, viscosity and air flow) are kept constant.
The average particles size is determined by weight method. Once we know the density, the number and the mass of a given number of particles and assuming perfect spherical shape we can calculate the average diameter of particles.

Nine groups of particles are obtained, their properties are given in Table B-1.

Table B-1: Ferrite and alginate properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Powder Size (μm)</th>
<th>True density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrite</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Keltone HV (sodium alginate)</td>
<td>180</td>
<td>1.59</td>
</tr>
</tbody>
</table>
APPENDIX C
VOLTAGE - INTENSITY CALIBRATION CURVE FOR
THE MAGNETIC FIELD GENERATOR

The voltage - intensity (U - I) calibration curve for the magnetic field generator (power supply, copper coil, connecting wires) is displayed in Figure C-1. It is a linear function of U. The inverse of the slope gives the resistance of the whole electric circuit:

\[ R = \frac{U}{I} \]  

(Eq. C-1)

Figure C-1: Voltage - intensity (U - I) calibration curve for the magnetic field generator
The $U_0\Delta P$ calibration curve for the orifice meter is displayed in Figures D-1. It is a quadratic function of $\Delta P$:

$$y = -0.0145x^2 + 0.9135x$$

$R^2 = 0.9887$

Figure D-1: Calibration curve for the orifice meter