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Abstract
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Keywords
computed tomography, fluidized bed, gas holdup, repeatability, x-rays, x-ray tomography

Disciplines
Acoustics, Dynamics, and Controls | Complex Fluids | Fluid Dynamics

Comments
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REPEATABILITY OF GAS HOLDUP IN A FLUIDIZED BED USING X-RAY COMPUTED TOMOGRAPHY

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ABSTRACT

Characterizing the hydrodynamics in fluidized beds is important to many processes from producing biofuels to coating pharmaceuticals. X-ray computed tomography (CT) can quantify local time-averaged phase fractions in multiphase systems that are highly dynamic, like fluidized beds. This paper describes the calibration methods used to produce CT images of a 15.24 cm diameter fluidized bed, how in-house software used these CTs to calculate gas holdup, and how well multiple CTs of a dynamic fluidized bed produced repeatable results while varying bed material and superficial gas velocities. It was concluded there is a very high degree of repeatability using the calibration methods and in-house software developed.

Keywords: computed tomography, fluidized bed, gas holdup, repeatability, X-rays, X-ray tomography

INTRODUCTION

Process industries such as energy, chemical, mineral, and pharmaceutical production have used fluidized beds for a wide array of processes such as mixing, drying, and catalytic cracking. Fluidized bed reactors are preferential for these processes because of their ability to provide low pressure drops, uniform temperature distributions, and high heat and mass transfer rates [1]. These fluidized bed characteristics are the result of bed material circulation by large dynamic voids of interstitial gas (i.e., bubbles). Understanding the dynamics of the gas-solid bed is key to improving design and scale up for industrial applications. While flow patterns inside the bed are known to significantly affect bed operation, the study of the bed hydrodynamics is problematic at best and, at times, impossible [2].

One application of fluidized bed use and the importance of hydrodynamics is in the biofuels industry where fluidized beds are used to extract useful energy from biomass through fast-pyrolysis and gasification [3]. During gasification, biomass will undergo a thermochemical conversion into usable hydrocarbon gases as it moves through a hot, dynamic, inert catalyst bed such as refractory sand [3]. When cleaned, these gases are called synthesis gas (syngas) and can be used as fuel for transportation, electricity production, and heating [4]. The hydrodynamics of the fluidized bed have a considerable influence on the thermochemical conversion efficiencies during biomass gasification and requires more research.

Bed hydrodynamics can be studied through invasive or noninvasive techniques. It has been shown that immobile objects such as baffles or invasive probes can dramatically alter hydrodynamics, therefore, non-invasive techniques are more favorable for dynamic observations [5]. Optical methods of observation are difficult to implement because of the opaque nature of the reactor and bed materials, yet have been used by Goldschmidt et al. [6] using a small, thin rectangular reactor made of transparent acrylic. Moreover, optical methods are impractical because internal flow structures are difficult to visualize [2]. Local variations in the system electrical properties are used in capacitance tomography, which has a good temporal resolution but generally has a coarse spatial resolution, is sensitive to the reconstruction algorithm, and may be influenced by electrostatic buildup that can be found in fluidized beds [7]. X-ray absorption, γ-ray absorption, or
positron emission tomography utilize penetrating radiation to observe the internal structures of an opaque object without disrupting any dynamic behavior through inherent properties of matter such as density [8]. These techniques can visualize flow patterns through the opaque materials in ways very similar to visible light by examining how the radiation is absorbed by the dense material. However, these methods have problems such as safety, expense, and limited resolution [9].

X-ray computed tomography (CT) can be used to map the 3D characteristics of the local gas fraction in fluidized beds. This technique was used by Grassler and Wirth [7] to observe local solids distributions in circulating fluidized beds. Solids concentrations were accurately measured to 20 vol% with spatial resolutions of 0.2 mm and errors of approximately 5%. Wu et al. [10] studied the fluidization characteristics of polyethylene resin in 3 fluidized beds of different diameters and concluded that fluidization hydrodynamics can be significantly affected by bed scale.

Fluidized bed scale up is a significant concern in system design. It has been shown that wall effects become more pronounced as the reactor diameter decreases and complex hydrodynamics are not predicted with CFD simulations [10, 11]. Use of X-ray CTs to research fluidized beds can give an accurate quantitative picture of the complex hydrodynamics. This paper shows that X-ray CT systems can provide repeatable time-averaged hydrodynamic information from highly dynamic fluidized beds.

X-RAY IMAGING CONSIDERATIONS

An X-ray imaging device records a two-dimensional projection of a three-dimensional object when the object is placed between an X-ray source and detector. The recorded image is actually a map of the X-ray attenuation through the object and is called a radiograph. X-ray computed tomography (CT) imaging generates a two-dimensional cross-sectional image of an object showing internal details. In this imaging process, an X-ray source illuminates the object of interest and projects the resultant X-ray intensity onto an imaging device (a single radiograph). Projections from several hundred orientations are collected and reconstructed with standard algorithms (to be discussed below) generating an image of the object cross-section. Since it takes time to acquire several hundred projections by either rotating the object or X-ray source/detector pair, X-ray CT scans are necessarily time-averaged. This section summarizes some of the considerations in X-ray imaging and in reconstructing a CT image.

X-ray Fundamentals

X-rays can be generated over a range of energy levels. In the keV to MeV range, electromagnetic radiation is classified as photons (characteristic) or waves (continuous). Characteristic X-rays are produced by atomic interactions of bound electrons emitted from the electron cloud. Continuous X-rays are produced by the acceleration or deceleration of charged particles, such as free electrons or ions. X-rays interact with matter in one of four ways that are described below.

X-rays interact with specific atoms through the nucleons, electrons and the electric field surrounding the electrons, and the meson field surrounding the nucleus [9]. These interactions include X-ray absorption, inelastic scattering, or elastic scattering. The only interactions truly important to radiography, listed in order of energy level, are the photoelectric effect, Compton scattering, and pair production.

An X-ray that is incident on an atom as a whole produces the photoelectric effect. The entire atom absorbs the X-ray, and to conserve energy and momentum, an electron is expelled. The atom then decays to a lower energy state and emits a characteristic X-ray. The photoelectric effect dominates at lower energy levels and absorption is highly dependent on material atomic number which scales roughly with density [9]. As an electromagnetic process, X-ray energy is reduced at each absorption-emission step but the decay can occur as many times as the X-ray energy allows.

If an X-ray is incident with a single electron, a loss of energy occurs through inelastic scatter, otherwise known as Compton or incoherent scattering. After the X-ray-electron collision, the electron recoils to conserve energy and momentum, scattering the X-ray in a different direction. This type of scatter is the main contributor of background radiation and can be problematic when quantifying the X-ray detector signal strength [9]. Compton scattering is dominant at intermediate energy levels and varies with atomic number per unit mass. As with the photoelectric effect, this process reduces the X-ray energy and can occur as many times as the X-ray energy allows.

An electron-positron pair is produced when an X-ray is incident with the electric field of an atom and disappears. To conserve energy and momentum, the electron-positron pair is created; however, the positron eventually interacts with another electron, annihilating each other, producing what is known as annihilation radiation [9]. The process that produces annihilation radiation is not a part of pair production, yet can be detected by an X-ray detector or produce any of the other electromagnetic phenomena discussed.

The ability to penetrate and/or pass through dense and/or opaque materials makes X-rays highly valuable from a diagnostic standpoint. As discussed above, X-rays are absorbed or attenuated in various ways depending on the atomic number of the material through which they pass, and the atomic number is related to material density. By quantifying the X-ray attenuation, a measure of the material density can be found through line integration along the X-ray beam path [12]. The attenuation of the X-ray is proportional to the material density and thickness; therefore, dense thick materials attenuate more.

X-ray CT Basics

X-rays energetic enough to pass through the object of interest, and that are incident on a detector like a scintillation unit, will cause the unit to fluoresce. The amount of
fluorescence is directly proportional to the incident X-ray energy and, therefore, a good approximation of the density of the material through which the X-ray passed. This fluorescing image, and by extension the attenuation, can be recorded by a camera system such as a charged couple device (CCD). The digital image can be processed and stored for later reconstruction into a digital 3D computed tomographic (CT) image.

X-ray CT is the process of examining the attenuated X-rays that have passed through an object to recover an estimate of its internal structure. The spatial, temporal, and density resolutions of CT scanners are key to defining internal structures of the object of interest like a fluidized bed. Spatial, temporal, and density resolutions are measured by the minimum distance separating two high contrast point projections, the frequency over which images can be obtained, and the smallest difference of mass attenuation coefficients the system can distinguish, respectively [12].

The reconstruction of a CT is completed by parsing the object into many individual images (radiographic projections) taken around the object with a fixed axis of rotation and then reconstructing the projections into a coherent 3D digital image. Consequently, if the system is dynamic, i.e., a bubbling fluidized bed, then the reconstructed image is necessarily time-averaged. For example, in our study an image was taken at every degree as the source and detector combination were rotated 360 degrees around the vertical axis of the fluidized bed. Each image had an exposure time of 1 second for a total of 360 seconds of fluidization time.

There are many possible algorithms used for CT reconstruction; a filtered back projection algorithm was used in this study. The quality of a CT image depends on the quality of data generated by the detector. Sources of CT inaccuracies are the intrinsic statistical variations due to the finite number of photons measured by the detector, as well as the particular instrumentation and processing errors from individual pieces of equipment [9]. Statistical noise manifests as random variations superimposed on the resulting CT image, limiting the contrast discrimination. This can be reduced by increasing the signal through increased exposure time, X-ray output, or source and detector size.

Pseudo-physical features or “imaging artifacts” within a CT image are large sources of error when making quantitative measurements from CT images. Artifacts come from two distinct sources, beam hardening and interface density changes [9]. Beam hardening results in a false radial density gradient that causes abnormally low values in the center of a uniform object and high values at the edges. Beam hardening is caused by the average radiation energy increasing as the X-rays propagate through an object because the low energy photons are preferentially absorbed. Interface density changes or edge artifacts come from sharp changes in signal level resulting in streaks in the CT due to mathematical relations in the reconstruction algorithm.

Another consideration in CT imaging is how the detector/camera system responds to X-ray intensity. Pixel response uniformity must be accounted for when properly reconstructing CT images. Ideally, when X-rays are incident on an imaging system, each pixel will react identically to the same level of X-ray intensity. However, due to inherent detector characteristics, pixel-to-pixel response variation will be present. First, the scintillation screen may have local response variations to X-ray intensity. Second, the pixel signal variations in the CCD array result from response variation of the CCD elements when subjected to a uniform light intensity. If these nonuniformities are not properly accounted for, ring artifacts that appear as full or partial circles around the center of rotation will be present in the resulting CT image [13].

System design and post processing practices can drastically reduce these sources of error.

**EXPERIMENTAL SETUP**

**Fluidized Bed Reactor**

A schematic of the fluidized bed reactor used in this study is shown in Figure 1. It is fabricated from a 15.24 cm internal diameter clear acrylic tube with a 1.5 mm thick stainless steel aeration plate inserted between the plenum and bed chamber. The aeration plate contains 132 1 mm diameter holes drilled in concentric circles giving the aeration plate an open area ratio of 0.57%. Air is introduced into the system by an inlet in the bottom of the plenum, which is filled with glass marbles to evenly disperse the air over the bottom of the aeration plate. Rubber gaskets are placed between each flange, sealing the various components and forcing all gas to flow directly through the bed and out the top. A pressure tap in the bottom of the plenum holds a transducer connected to a computer controlled data acquisition card to record inlet pressure. A second tap on the side of the fluidized bed 3 cm above the aeration plate is used for particle and air injection and not used in this study. The reactor is placed precisely in the middle of the X-ray imaging facility and held firmly in place by a pair of C-clamps to reduce bed vibration.
FIGURE 1: SCHEMATIC OF THE FLUIDIZED BED REACTOR.

Bed Material

The fluidized bed materials used in this study were glass beads and crushed walnut shell, both in the 500-600 \( \mu \text{m} \) size range. Particle size ranges were obtained through sieving with a shaker unit, and the glass beads were also washed to assure they were contaminant free, providing the most accurate bulk density and bed weight. Both particles fall within the Geldart type-B size range [14]. Images of these materials at 10 times magnification are shown in Figure 2. As expected, glass beads are much more uniformly shaped than crushed walnut shell. A summary of the bed characteristics used in this study is provided in Table 1.

X-ray Flow Visualization Facility

The X-ray flow visualization facility at Iowa State University has been described in detail elsewhere [13]; only a summary is described here. A dual source/detector combination, mounted as shown in Figure 3, is used to produce the X-ray CT images. The image intensifier in Figure 3 was not used in this study. Each X-ray source is a LORAD LPX200 unit with adjustable voltage (10-200 KeV) and current (0.1-10 mA) capabilities. A single 44 x 44 cm cesium iodide scintillation screen transforms the X-ray energy into visible light which is imaged by an Apogee Alta U9 CCD camera system with a 50 mm, variable exposure rate Nikon lens. The camera has a 3072 x 1024 active pixel matrix, however, by combining pixels into 4 x 4 clusters, the active pixel matrix was reduced to 768 x 512 for an effective spatial resolution of approximately 0.6 mm. This reduced the data file size and acquisition time considerably.

TABLE 1: BED MATERIAL PROPERTIES.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Walnut</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Density</td>
<td>[kg/m(^3)]</td>
<td>567</td>
<td>1496</td>
</tr>
<tr>
<td>Bed Weight</td>
<td>[g]</td>
<td>1576.3</td>
<td>4158.2</td>
</tr>
<tr>
<td>Particle Density</td>
<td>[kg/m(^3)]</td>
<td>1300</td>
<td>2600</td>
</tr>
<tr>
<td>Bulk Void Fraction</td>
<td>[-]</td>
<td>0.56</td>
<td>0.42</td>
</tr>
</tbody>
</table>

FIGURE 2: GLASS BEADS (a) AND CRUSHED WALNUT SHELL (b).
Compton Scattering

Compton scattering appears as image blurring and can be reduced by increasing the detector distance from the object being imaged. As the detector is moved further away from the object that X-rays are passing through, less Compton scattering will be observed in the radiograph. The more collimated the X-ray beam, the more well defined the object edges in the radiographs resulting in a better CT reconstruction. By simply adjusting the source and detector position, considerable amounts of Compton scatter can be reduced; however, small amounts will always be present.

Pixel Normalization

Each CCD camera pixel element is different because of small imperfections within the CCD substrate due to manufacturing tolerances. The imperfections result in a different non-linear response of each CCD element to incident X-ray power. Therefore, as the incident X-ray energy on the detector changes, the CCD camera must be calibrated to account for nonuniform response.

To calibrate the CCD camera, two images are taken, one with and one without X-rays being emitted from the source; these are termed light and dark images, respectively. Before the light image is taken, the camera position and source power settings are defined for a particular fluidized bed setup. The source element changes over time and temperature, and must come to steady-state by letting it run at full power for a prescribe amount of time. To identify the correct X-ray power setting for a particular bed material, images of the fluidized bed running at a specified velocity are taken and fine tuned by adjusting the camera position and source power settings. The light image is then taken at the fixed camera position after the cesium iodine phosphor screen is exposed over a long time period to the prescribe X-ray power setting. The fluidized bed is removed from the imaging region for this calibration data.

The dark image is taken before the X-ray power source is powered on, ensuring no residual light emitted from the phosphor screen. These two images are then used to normalize the pixel response through an algorithm described by Striegel [15].

Beam Hardening

Beam hardening corrections are completed in two steps. First, by filtering low energy X-rays emitted from the source with two 0.6 mm thick copper plates and one 1.5 mm thick aluminum plate. Second, by analyzing the X-ray attenuation of the same material at varying thicknesses as described by Franka [16]. The analysis yields a 5th order polynomial curve fit and is applied to CT data before being reconstructed. For this study, a beam hardening correction is applied only to the glass beads because beam hardening in crushed walnut shell is assumed to be negligible.

DATA ANALYSIS

Gas Holdup Calculations

The gas holdup (void fraction or volumetric gas fraction) describes the amount of voidage in the bulk material. Quantifying the time averaged local gas holdup, \( \varepsilon_g \), requires a CT of the empty reactor (\( CT_e \)), a CT of the reactor filled with a fixed bed of the bulk material (\( CT_b \)), and a CT of the reactor under specified fluidization conditions (\( CT_r \)). For this study the fluidization condition for both glass beads and crushed walnut shell were \( U_g = 1.5 U_{mf} \) and \( U_g = 3 U_{mf} \), where \( U_{mf} \) is the minimum fluidization velocity for the respective bed material. To ensure the same response for each material from the detector system, each CT is taken with the same X-ray source power settings for the respective material.

The local time-averaged gas holdup is then determined from the two reference CT images and the flow CT image:

\[
\varepsilon_g = \frac{CT_f - CT_b + CT_g - CT_f}{CT_g - CT_b} \varepsilon_{g,b} \tag{1}
\]

where the bulk void fraction, \( \varepsilon_{g,b} \), is defined as:

\[
\varepsilon_{g,b} = 1 - \frac{\rho_b}{\rho_p} \tag{2}
\]

where \( \rho_b \) and \( \rho_p \) are the bulk and particle density, respectively. The bulk density is determined experimentally and the particle densities are given by the manufacturer. This calculation results in a 3D image mapping the time-averaged gas holdup in the reactor.

3D Image Analysis

Each CT image is processed using custom software. The reconstructed 3D images of the fluidized bed can be sliced to show internal structure of the dynamic bed as shown in Figure 4. Because the voxels hold intensity data, the slice images are in gray scale; however, images can have a false color applied
to improve contrast. All analysis reported in this study will only evaluate signal response of the system to quantify repeatability along the planar slices in Figure 4.

\[ \text{FIGURE 4: CT IMAGING PLANES.} \]

RESULTS AND DISCUSSION

Minimum Fluidization Velocity

Fluidization is the act of passing a liquid or gas through a bed of solid granular material at such a rate that the material acquires dynamic properties similar to a fluid. An incipiently fluidized bed is the point at which the material obtains fluid properties. The superficial gas velocity \( U_g \) at which this occurs is the minimum fluidization velocity \( (U_{mf}) \). Quantifying \( U_{mf} \) is done empirically and is discussed by Franka et al. [17].

For glass bead fluidized beds in the reactor described in Figure 1, \( U_{mf} = 19.5 \pm 0.7 \text{ cm/s} \), while \( U_{mf} = 18.1 \pm 0.2 \text{ cm/s} \) for ground walnut shell.

Gas Holdup Repeatability

Repeatability was determined by acquiring time-averaged local gas holdup data five different times for the same test conditions (two different materials and two different flow rates) to encompass a range of material densities and gas flow rates. Hence, local \( c_g \) values were extracted from each of the 20 3D \( c_g \) maps in both the x-z and y-z planes. Local \( c_g \) values were also used to determine the average planar gas holdup in each x-y plane as a function of height for each 3D mapping. The standard deviation of the average planar gas holdup as a function of height is also included. Because of the large volume of data, only selected results are presented here. The data show repeatability on a local level across the bed at different axial heights \((c_g \text{ vs. axial radial position})\), repeatability averaged across the bed at every measurable height \((h/D \text{ vs. } c_g)\), and repeatability in the fluctuations at different axial heights \((h/D \text{ vs. standard deviation } \sigma)\).

As shown in Figures 5-8, high repeatability among all testing groups is observed for both glass beads and crushed walnut shell. Figures 5 (glass beads) and 7 (crushed walnut shell) show the local \( c_g \) plotted as a function of radial position at (a) \( h = 0.5D \) and \( U_g = 1.5U_{mf} \), (b) \( h = 0.7D \) and \( U_g = 3U_{mf} \), (c) \( h = 1D \) and \( U_g = 1.5U_{mf} \), and (d) \( h = 1D \) and \( U_g = 3U_{mf} \). The graphs show that gas holdup is fairly uniform across the bed in both the x-z and y-z planes. They also show that for all five tests, \( c_g \) is approximately the same, including similar features across the bed. The feature similarity is partially due to the gas holdup calculations (Eq. (1)) using the same bulk and empty bed CT information. Noise in these CTs carries over because of the method of calculating \( c_g \); however, the local variations across the bed appear to be low. A slight dip in \( c_g \) near the bed wall in Figures 5 and 7 is due to a cropping error in the CTs (i.e., the region of interest (ROI) captures a small portion of the reactor wall causing incorrect \( c_g \) values).

Figures 6 (glass beads) and 8 (crushed walnut shell) show the average planar \( c_g \) plotted as a function of height at (a) \( U_g = 1.5U_{mf} \) and (b) \( U_g = 3U_{mf} \) and the standard deviation of the average planar \( c_g \) plotted as a function of height at (c) \( U_g = 1.5U_{mf} \) and (d) \( U_g = 3U_{mf} \). Graphs (a) and (b) in Figures 6 and 8 show a high degree of agreement with those of Figures 5 and 7 by the fact that they both show very little variation in the calculated \( c_g \). This is apparent by the tight grouping among each test. Small deviations do exist but are attributed to local variations in the two systems. One general observation is that glass bead beds have more consistent results between tests; this is due to the fact that the glass bead system is better characterized and more uniform than the (natural) ground walnut shell system. Also, higher superficial gas velocities generally produce more uniform results between tests because the systems are better mixed at the higher gas flow rates. Finally, the local values also show smaller variations towards the top of the fluidized bed (e.g., \( h = 1D \)) because the mixing is better in this region and any nonuniformities resulting from (potentially) unsteady inlet conditions are suppressed.

Figure 6 and 8 graphs (c) and (d) show the standard deviation of the average planar gas holdup plotted as a function of height for \( U_g = 1.5U_{mf} \) and \( U_g = 3U_{mf} \), respectively. Only small variations in the planar standard deviations are observed implying fluctuations in the x-y plane remain similar from test-to-test.

CONCLUSIONS

Time averaged local gas holdup was studied for two different bed materials and superficial gas velocities. Each bed material and superficial gas velocity was tested five times to show repeatability of gas holdup calculations using quantifiable CT data. The results for both bed materials at both superficial gas velocities showed a very high degree of repeatability in quantifying time-averaged local gas holdup through CT analysis. Glass bead bed tests show more consistency because of better material characteristics and, therefore, have a higher degree of repeatability than a crushed walnut shell bed. Higher superficial gas velocities also show better repeatability for both bed materials because of mixing characteristics of the bed. The suppression of unsteady inlet conditions also gives smaller variations in the local gas holdup values for each material near the surface of the bed.
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REFERENCES


FIGURE 5: LOCAL GAS HOLDUP PLOTTED AS A FUNCTION OF RADIAL POSITION FOR GLASS BEADS AT (a) $h = 0.5D$ and $U_g = 1.5U_{mf}$, (b) $h = 0.5D$ and $U_g = 3U_{mf}$, (c) $h = 1D$ and $U_g = 1.5U_{mf}$, and (d) $h = 1D$ and $U_g = 3U_{mf}$. 

Material: Glass
Size: 500 - 600 μm
Bulk Void Fraction: 0.60
Bulk Height: 15.24 cm
$U_m = 13.5$ cm/s
$Q_1 = 0.02
h = 0.500$
Figure 6: Average planar gas holdup plotted as a function of height for glass beads at (a) $U_g = 1.5U_{mf}$ and (b) $U_g = 3U_{mf}$, and the standard deviation of the average planar gas holdup plotted as a function of height for glass beads at (c) $U_g = 1.5U_{mf}$ and (d) $U_g = 3U_{mf}$. 
FIGURE 7: LOCAL GAS HOLDUP PLOTTED AS A FUNCTION OF RADIAL POSITION FOR CRUSHED WALNUT SHELL AT (a) $h = 0.5D$ and $U_g = 3U_{mf}$ (b) $h = 0.5D$ and $U_g = 1.5U_{mf}$, (c) $h = 1D$ and $U_g = 1.5U_{mf}$, and (d) $h = 1D$ and $U_g = 3U_{mf}$.
FIGURE 8: AVERAGE PLANAR GAS HOLDUP PLOTTED AS A FUNCTION OF HEIGHT FOR CRUSHED WALNUT SHELL AT (a) \( U_g = 1.5U_{mf} \) and (b) \( U_g = 3U_{mf} \), and THE STANDARD DEVIATION OF THE AVERAGE PLANAR GAS HOLDUP PLOTTED AS A FUNCTION OF HEIGHT FOR CRUSHED WALNUT SHELL AT (c) \( U_g = 1.5U_{mf} \) and (d) \( U_g = 3U_{mf} \).
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