

Fluidization Characteristics of Sand and Chopped Switchgrass-Sand Mixtures

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ABSTRACT

A laboratory, fluidized-bed gasifier is being researched as a means to gasify feedstocks in a process to produce ethanol from biomass. Fluidization characteristics of the bed, especially minimum (U_{mf}) and complete (U_{cf}) fluidization velocities, were measured because they are critical to the operation of the gasifier. Fluidization properties of sand and chopped switchgrass-sand mixtures of different particle sizes and bulk densities were studied in this work. Experiments were performed in a 250-mm ID, fluidized-bed, clear plastic column that was dimensionally identical to the laboratory gasifier. The percentages of chopped switchgrass in the mixtures studied were 1.0, 2.0, 2.9, 4.8, 6.5 and 8.3% by weight. Sand particle sizes studied had geometric mean diameters (GMD) of 375, 381, 450, 621 and 863 μm . The U_{mf} and U_{cf} values were more sensitive to the sand particle size than to the percent switchgrass level in the switchgrass-sand mixtures. The U_{cf}/U_{mf} ratio decreased with an increase in the percent weight of switchgrass. The descriptions of the behavior of the fluidized bed are also included in this study.

Keywords: Fluidization characteristics; Switchgrass; Sand; Fluidized-bed; Gasification.

1. INTRODUCTION

Switchgrass is one of the potential biomass feedstocks in the U.S. for generation of liquid fuels such as ethanol. Part of the conversion can be conducted through biomass gasification. Fluidized-bed gasifiers have many advantages over fixed-bed gasifiers, including good gas-solids contact, better temperature control, and excellent heat transfer characteristics. Oklahoma State University has a research project to convert chopped switchgrass into synthesis gas (syngas) through fluidized-bed gasification. Syngas can then be supplied to a bioreactor for conversion into ethanol. Knowledge of the fluidization characteristics of solids participating in the fluidized-bed gasification reactor, primarily inert sand and mixtures of chopped switchgrass and sand, is crucial not only in designing the reactor, but also for proper tuning of the process parameters to generate high-quality syngas. Velocities for minimum fluidization (U_{mf}), and complete fluidization (U_{cf}) are among those fluidization properties that must be understood.

Fluidization correlations for predicting minimum fluidization velocity and fluidized bed expansion ratio for coal gasification materials have been studied, and an empirical correlation model has also been developed (Babu et al., 1978). Minimum and complete fluidization velocities for mixtures of biomass fuels (namely rice husk, sawdust, peanut shell powder, pine

wood chips, straws, and thistle) with sand have been experimentally determined and correlations developed (Pilar et al., 1992; Rao and Bheemarasetti, 2001).

However, no work has been reported on fluidization characteristics of the switchgrass-sand mixtures. Therefore the present study was conducted to determine velocities for minimum and complete fluidization of sand and the chopped switchgrass-sand mixtures.

2. MATERIALS AND METHODS

2.1 Chopped Switchgrass Particle Size Analysis

Switchgrass, at approximately 10% (wet basis) moisture content, was chopped in a Haybuster H-1000 tub grinder (DuraTech Industries International, Inc. Jamestown, ND), with a screen of 25-mm sieve size and placed into a storage container. Representative samples of chopped switchgrass were taken from the storage container, one each from the top, middle and bottom thirds respectively. Switchgrass samples were classified by screening according to the ASAE standard for forage materials (ASAE, 1998). Two sieving setups were used. A chopped switchgrass sample of 7% wet basis moisture content and known weight was first sieved with four screens having square openings and with diagonal lengths of 5.4, 5.0, 4.6 and 4.1 mm respectively. These screens were installed in a mechanical shaker (Screen Vibrator, Seedbuo Equipment Company, Chicago, IL). The duration of sieving was set at 3 minutes. The material that passed through the fourth screen was subjected to particle-size distribution analysis using USA standard testing sieves (Nos. 7, 10, 12, 16, 25, 30, 50 and 100) for five-minute duration.

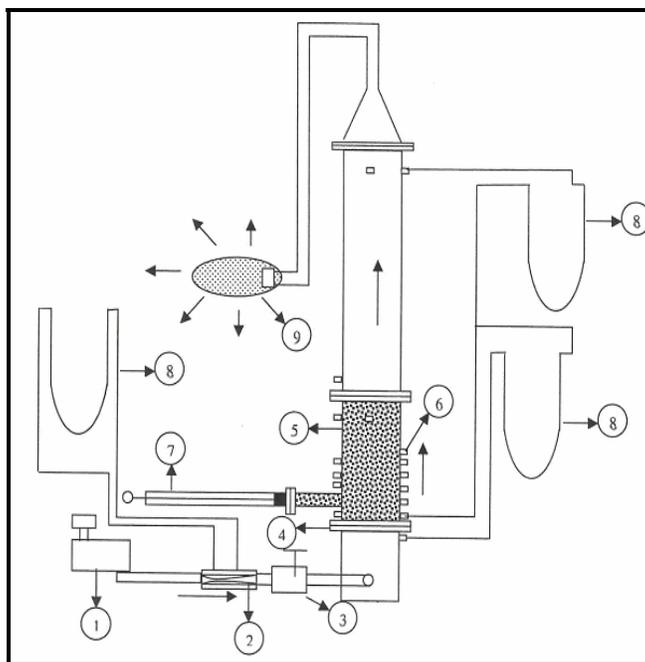
Observations of mass retained on each screen, covering both setups, were used to determine percent mass distribution of the chopped switchgrass sample. Geometric mean length of the sample and geometric standard deviation of particle length by mass were calculated as per ANSI/ASAE S 424.1 MAR98 (ASAE, 1998). Length, width, and thickness of the particles retained on each screen were measured manually with a digital caliper (Digimatic, Mitutoyo, Japan) having a resolution of 0.1 mm. This rigorous exercise gave the particle size profile. The whole chopped switchgrass was subjected to bulk density measurements. In each case, the material was poured into a 473-ml container (One pint model, OHAUS Corp., Pine Brook, NJ) from 100 mm above and weighed. The bulk density was determined by dividing the weight of the material by the volume of the container.

2.2 Sand Particle Size Analysis

Silica sand (Oglebay Norton Industrial Sands, Inc., Brady, TX) was used in the study. ANSI/ASAE S319.3 JUL97 (ASAE, 2000) was adopted to experimentally determine the particle-size distribution of sand samples. A motorized sieve shaker (CSC Scientific, Fairfax, VA) was used to automate the sieving process. The duration of sieving was set at 5 minutes. Sand samples of different particle size distributions were prepared. Geometric mean diameter (GMD) of the sand sample and geometric standard deviation of particle diameter by mass were calculated. Bulk density values were determined. The procedure adopted and equipment used for the bulk density measurements were the same as stated in the previous section.

2.3 Fluidized-Bed Setup and Instrumentation

The fluidized-bed was constructed identically to the fluidized-bed gasifier being tested at Oklahoma State University, Stillwater, OK, in terms of all dimensions. A schematic of the experimental setup is shown in Figure 1.



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|--|----------------------------------|
| 1- Electric blower with variable frequency drive and air filter, | 5- Fluidized-bed, |
| 2- Venturi meter, | 6- Ports for pressure/internals, |
| 3- Temperature sensor, | 7- Plunger based biomass feeder, |
| 4- Air distributor, | 8- U tube manometer, |
| | 9- Filter bag |

Figure 1. Schematic of the fluidized-bed setup.

The major components of the fluidized-bed setup included an air blower (5HVF, Fuller company, Sutorbilt Products, Compton, CA) coupled to a variable frequency drive (Pacemaker, The Louis Allis Co. Milwaukee, WI), a custom-made venturimeter for air flow measurement, a thermo-anemometer (VelociCalc 8350, TSI Incorporated, St. Paul, MN) for air velocity and temperature measurement, a custom-made PVC fluidization column, custom-made U tube manometers for pressure measurements, a thermo-hygrometer (Fisher Scientific, Hampton, NH) for the measurement of atmospheric air temperature and relative humidity, and a vacuum-cleaner filter bag (Great Value brand, Y Type Microfilter, Wal-Mart Stores, Inc., Bentonville, AR) for capturing elutriated mass. Air distribution in the column was accomplished using a 5-mm thick, PVC plate with 177 evenly spaced and 2-mm diameter holes.

2.4 Test Procedure

The procedure adopted for fluidization tests was based on extensive review of similar work reported in the literature (Pilar et al., 1992; Rao and Bheemarasetti, 2001). Before each

experimental run, the system was tested for air leaks, which were immediately repaired using silicone sealant (Silicone II, GE Sealants and Adhesives, Huntersville, NC). Silica sand (described above) was used as the inert bed material. The sand-alone fluidization tests were conducted with a sand bed weight of 20 kg. For the tests on the chopped switchgrass-sand mixtures, the sand weight of 20 kg was kept constant. The switchgrass weight percent levels in the mixtures were 1.0, 2.0, 2.9, 4.8, 6.5 and 8.3%. For proper mixing, sand and chopped switchgrass were loaded in layers within the fluidized bed and thoroughly mixed by blowing the air through the bed before starting the experiments. The airflow rate was gradually increased to observe the bed behavior in the fluidization process. The airflow rate and temperature were monitored.

Other observations recorded include the pressure drops across the bed and across the venturi meter, velocity of the fluidization air, temperature and humidity of atmospheric air, and weight of the elutriated mass. Visual observations of the nature of fluidization were noted at each level of the airflow supplied. Once the bed reached complete fluidization (U_{cf}), the airflow rate was reduced in order to study the defluidization characteristics. Parameters identified above were recorded until the bed regained its original status.

2.5 Determination of fluidization velocities

Minimum fluidization velocity (U_{mf}) was the superficial air velocity at which the pressure drop across the fluidizing bed became constant. U_{cf} was determined based on visual observations of the superficial air velocity at which the entire bed started fluidizing vigorously. Photographs of the bed were taken at various stages of fluidization (Figure 2).

The segregation of biomass particles and slugging of chopped switchgrass-sand bed were determined on the basis of visual observations.



Figure 2. Reactor bed at minimum (left) and complete (right) fluidization velocities.

3. RESULTS AND DISCUSSION

3.1 Particle Size Distribution and Physical Properties of Chopped Switchgrass

The percent mass distribution and physical properties of chopped switchgrass are shown in Table 1. Results indicate that the average particle length of the switchgrass varied as follows: approximately 65% (by weight) of the material ranged from 14.70 mm to 17.23 mm; 31% ranged from 2.18 mm to 7.80 mm; and 1% of the chopped mass had an average particle length of 27.24 mm. The remaining 3% of the chopped switchgrass was powdery (less than 2.18 mm in length). The geometric mean length of the sample and the geometric standard deviation of the particle length were 3.07 mm and 2.38 mm, respectively. It seemed that the adopted procedure, which was based on ASAE standard for forage materials, substantially underestimated the particle length parameter for chopped switchgrass. The average bulk density value for the chopped switchgrass was 138 kg/m³.

Table 1. Percent mass distribution and physical properties of chopped switchgrass.

Screen No.	Sieve opening diagonal length, mm	Total on screens ^a % mass	Cumulative undersize % mass	Length ^b	Width ^b	Breadth ^b
1	5.4	1.03	98.97	27.24 ±11.16	2.78±1.34	1.24±1.16
2	5	59.25	39.72	17.23±8.83	1.93±1.10	0.62±0.54
3	4.6	0.94	38.77	17.21±7.92	1.25±0.83	0.29±0.21
4	4.1	3.81	34.96	11.02±6.60	0.73±0.57	0.22±0.16
5	3.95	0.34	34.62	14.7±6.76	0.58±0.51	0.18±0.12
6	2.83	3.24	31.38	7.8±4.47	0.44±0.37	0.15±0.09
7	2.36	2.13	29.24	5.88±3.49	0.56±0.47	0.2±0.16
8	1.68	4.01	25.24	4.52±2.53	0.36±0.37	0.15±0.10
9	0.99	11.49	13.75	2.63±1.56	0.29±0.25	0.14±0.11
10	0.85	3.95	9.8	3.01±0.99	0.27±0.22	0.1±0.02
11	0.42	6.9	2.91	2.18±1.04	0.3±0.22	0.12±0.04
12	0.21	2.28	0.63	Not measured	Not measured	Not measured
Pan	0	0.63	0	Not measured	Not measured	Not measured
Total		100				

^a average of 3 observations; ^b average of 75 observations

3.2 Physical Properties Of Sands

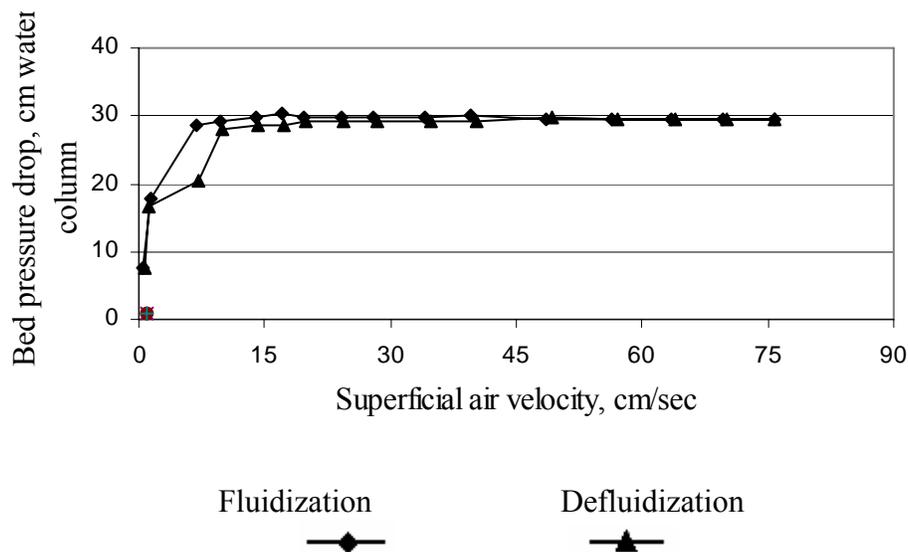
Physical properties of sands used in the study are shown in Table 2. The GMD varied from 375 to 863 μm while bulk density values varied from 1420 kg/m³ to 1596 kg/m³.

Table 2. Physical properties of sands.

	A	B	C	D	E
Geometric mean diameter (GMD), μm	375	381	450	621	863
Standard deviation, μm	1.48	1.12	N/A	1.08	1.31
Density (kg/m^3)	1596	1575	1567	1486	1420

3.3 Minimum Fluidization (U_{mf}) and Complete Fluidization (U_{cf}) Velocities of Sand

Bed pressure drop vs. air velocity curves for the different sand sizes were plotted both for increasing flow rates (fluidization) and decreasing flow rates (defluidization). A typical curve showing the variation of bed pressure drop with superficial air velocity for the sand size of 375 μm is shown in Figure 3. Pressure drop was higher on fluidization than on defluidization. It was evident because initially the bed was less permeable. Variation of U_{mf} and U_{cf} with the sand particle size is shown in Figure 4. Standard deviation error bars are also shown. Each value is the mean of a maximum of three observations. U_{mf} and U_{cf} mean values are in the range of 8.39-33.53 cm/sec and 64.25-76.44 cm/sec, respectively. Figure 4 reveals that as the sand particle size increased, both U_{mf} and U_{cf} also increased. The variation of complete to minimum fluidization velocity ratios (U_{cf}/U_{mf}) with sand size is shown in Figure 5 along with standard deviation error bars. U_{cf}/U_{mf} ratio varied from 2.29 for the sand with a GMD of 863 μm to 7.82 for the sand with a GMD of 375 μm . As compared to U_{cf} values, the U_{mf} values were drastically reduced at the lower sand size levels resulting in higher U_{cf}/U_{mf} ratios for lower sand size levels. The power function relationship was found to fit the data well. This trend matched those observed by other researchers (Pilar et al., 1992; Rao and Bheemarasetti, 2001).

Figure 3. Air velocity-bed pressure drop curves for silica sand (GMD=375 μm).

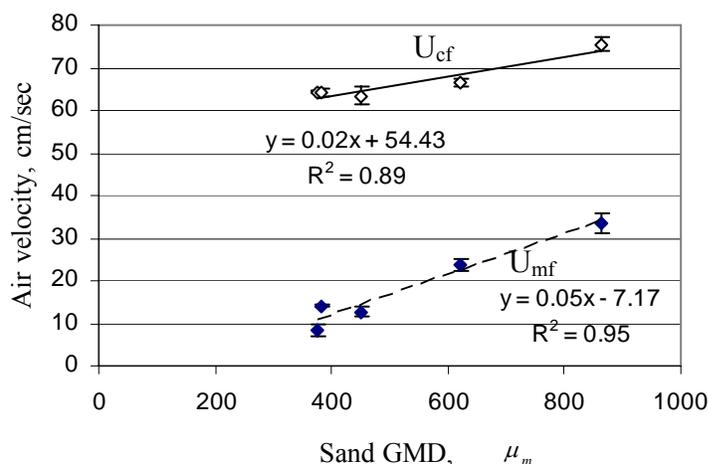


Figure 4. Variation of U_{mf} and U_{cf} with sand size

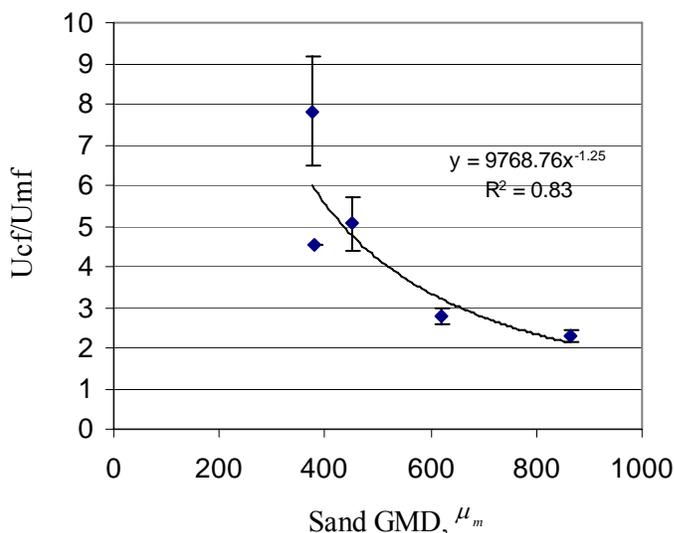


Figure 5. Variation of U_{cf}/U_{mf} ratio with sand size.

3.4 Minimum Fluidization (U_{mf}) and Complete Fluidization (U_{cf}) Velocities of Chopped Switchgrass-Sand Mixtures

The switchgrass weight percent levels in the mixtures were 1, 2, 2.9, 4.8, 6.5 and 8.3% respectively. The air velocity to bed pressure drop curve for the mixture with 1.0% (200 g) switchgrass is shown in Figure 6. During the fluidization process, the bed pressure drop values were higher when compared to those measured during the defluidization phase because initially, at the beginning of the fluidization experiment, the well-settled bed has less voidage and it is less permeable. As a result, during fluidization the bed pressure-drop values were high. A similar trend was observed for the other switchgrass-sand mixtures. In addition, previous studies of bed pressure drop vs. velocity relationships during fluidization and defluidization, described by Gupta and Sathiyamoorthy (1999) and Kunii and Levenspiel (1991), also supported the trend observed in this study.

U_{mf} and U_{cf} values were determined for each chopped switchgrass-sand mixture. Visual observations depicted in Figure 2 became the basis for determining the U_{cf} values. The variation of the means of U_{mf} and U_{cf} with percent weight switchgrass in mixtures is shown in Figure 7 along with standard deviation error bars. Each value is the average of two observations. U_{mf} values ranged from 10 cm/sec for the mixture with 1% switchgrass to 18.75 cm/sec for the mixture with 8.3% switchgrass. U_{cf} values varied from 64 cm/sec for the mixture with 1% switchgrass to 77 cm/sec for the mixture with 8.3% switchgrass. In other words, when the percent weight of switchgrass was increased 8-fold, the U_{cf} value increased 20%, revealing that for the mixtures of switchgrass with sand, both U_{mf} and U_{cf} values are less sensitive to the percent switchgrass than they are to sand sizes (Figures 4 and 5). It is shown in Figure 8 that the U_{cf}/U_{mf} ratios decreased with an increase in the percent weight of switchgrass in the mixture. Since the sand size, which is the major contributing factor for the change in fluidization velocities, was kept constant (375 μm), a linear relationship was found to fit the data well. The ratios are in the range of 4.13 for 8.3% switchgrass to 6.42 for 1.0% switchgrass in the mixtures with sand. The standard deviation error bars are also shown for U_{cf}/U_{mf} values in Figure 8.

At the end of every experiment on chopped switchgrass-sand mixtures, segregation of biomass particles on the top of the bed was observed. This occurred mainly because of the difference in the bulk densities of sand and biomass particles. Biomass segregation is very crucial for the systems like fluidized bed gasifiers because it results in the generation of localized high temperature spots. Another observation was bed slugging. When the level of the biomass in the mixtures was increased above 4.8%, no fluidization occurred only slugging. Large particle length and low bulk densities of the switchgrass as compared to sand are other factors responsible for bed slugging. Similar behavior was reported by Pilar et al. (1992) while studying the fluidization of different biomass materials with sand. Wu and Baeyens (1998) also reported segregation by size difference in gas-fluidized beds.

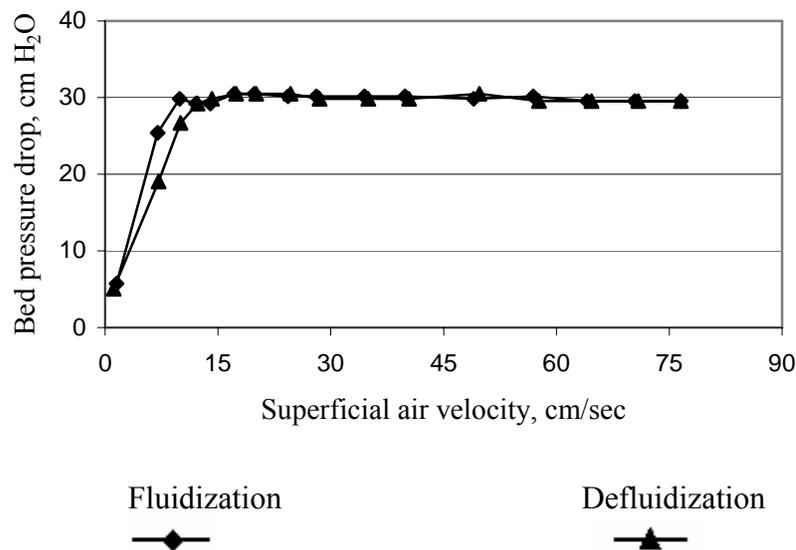


Figure 6. Air velocity-bed pressure drop curve for switchgrass-sand (375 μm GMD) mixture with 1% switchgrass.

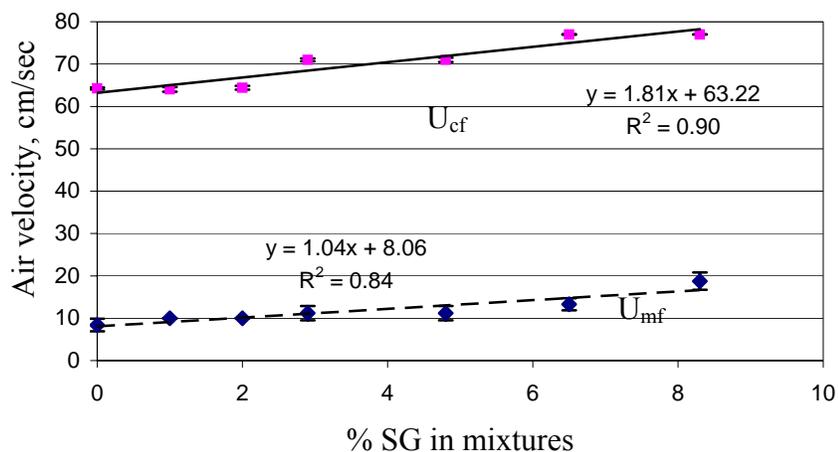


Figure 7. Variation of U_{mf} and U_{cf} with % weight of switchgrass (SG) in SG-sand ($375 \mu\text{m}$ GMD) mixtures

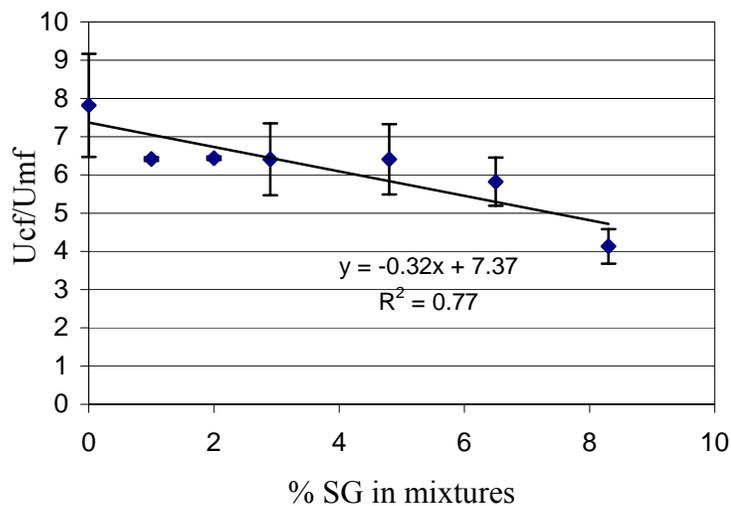


Figure 8. Variation of U_{cf}/U_{mf} with % weight of switchgrass (SG) in SG-Sand ($375 \mu\text{m}$ GMD) mixtures

4. CONCLUSIONS

1. The U_{mf} and U_{cf} values are more sensitive to the sand particle size as compared to the percent switchgrass level in the chopped switchgrass-sand mixtures.
2. During the fluidization process, the bed pressure drop values were higher when compared to those measured during the defluidization phase.
3. The U_{cf}/U_{mf} ratio decreased with an increase in the percent weight of switchgrass in the chopped switchgrass-sand mixture.
4. At the end of every experiment, segregation of biomass particles on the top of the bed was observed.
5. Slugging occurred at the higher levels (above 4.8%) of switchgrass in chopped switchgrass-sand mixtures suggesting a practical upper limit of switchgrass of less than 5% of the overall bed mass.

5. ACKNOWLEDGEMENTS

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