FLUIDIZATION AND MIXING CHARACTERISTICS OF BIOMASS PARTICLES IN A BUBBLING FLUIDIZED BED

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ABSTRACT

FLUIDIZATION AND MIXING CHARACTERISTICS OF BIOMASS PARTICLES IN A BUBBLING FLUIDIZED BED

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Fluidized bed is a suitable technology for combustion and gasification of biomass materials. Hydrodynamics occurring in the bed is crucial for the design and operation of the combustion or gasification unit. In the present study, hydrodynamic behavior of binary mixtures of biomass-silica sand in a bubbling fluidized bed was experimentally investigated. Five different biomass materials and silica sand with three different particle sizes were employed to form binary mixtures. Biomass materials were rice husk, sawdust, wheat straw, hazelnut shell and olive cake which are all potential energy sources for Turkey. Effects of mass percentage of biomass and particle size of silica sand on minimum fluidization velocity of the mixtures were determined. Comparisons between results of the present study and predictions of available correlations proposed for minimum fluidization velocity of binary mixtures were carried out. Mixing and segregation

characteristics of biomass-silica sand binary mixtures were investigated for mixtures having different mass fraction of biomass and different silica sand particle sizes. Fluidization and bubbling behaviors of mentioned mixtures were observed in a 2-D fluidized bed and images taken during steady-state operation of bed were presented as visual tools to guide fluidization characteristics of the bed.

Mass percentage increase of rice husk, wheat straw and sawdust resulted in increase in minimum fluidization velocity of the mixture whereas change in mass fraction of olive cake and hazelnut shell had no effect on minimum fluidization velocity. Minimum fluidization velocity increased with increase of silica sand particle size for all biomass-silica sand mixtures having same mass percentage of biomass. Vertical mixing pattern in the bed at steady state conditions were found almost same for all biomass-silica sand mixtures. Biomass acted as flotsam and accumulated mostly at the top of the bed and silica sand acted as jetsam and accumulated mostly at the bottom of the bed. 2-D bed experiments showed that mixing biomass materials with silica sand provides desired bubbling behavior in the bed.

Keywords: Fluidized bed, hydrodynamics, biomass.

ÖZ

BİYOKÜTLE PARÇACIKLARININ KABARCIKLI AKIŞKAN YATAKTAKİ AKIŞKANLAŞMA VE KARIŞIM KARAKTERİSTİKLERİ

İnanlı, Sinan
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Akışkan yatak, biyokütlenin yakılması ve gazlaştırılması için uygun bir teknolojidir. Yatak içerisinde meydana gelen hidrodinamik davranışın önceden bilinmesi, yakma veya gazlaştırma ünitesinin tasarımı ve çalışması için çok önemlidir. Sunulan çalışmada, biyokütle-silis kumu ikili karışımlarının kabarcıklı akışkan yataktaki hidrodinamik davranışları deneysel olarak incelenmiştir. Beş farklı biyokütle ve üç farklı parçacık büyüklüğüne sahip silis kumu ikili karışımları oluşturmak için kullanılmıştır. Kullanılan biyokütleler pirinç kabuğu, talaş, buğday sapı, fındık kabuğu ve zeytin posasıdır ve bu biyokütlelerin hepsi Türkiye için potansiyel enerji kaynaklarıdır. Yapılan çalışmada, biyokütlenin kütlesel yüzdesi ve silis kumu parçacık büyüklüğünün karışımın minimum akışkanlaşma hızı üzerindeki etkileri belirlenmiştir. İkili karışımların minimum akışkanlaşma hızı için literatürde bulunan korelasyonların sonuçlarıyla bu çalışmada elde edilen sonuçlar karşılaştırılmıştır. Farklı biyokütle oranına ve farklı silis kumu büyüklüğüne sahip biyokütle-silis kumu ikili karışımlarının karışım ve ayrışma karakteristikleri incelenmiştir. Belirtilen karışımların akışkanlaşma ve kabarcık davranışları 2-boyutlu akışkan yatakta gözlemlenmiş ve yatak kararlı durumda çalışırken elde edilen görüntüler yatağın akışkanlaşma kalitesini sergileyen görsel öğeler olarak sunulmuştur.

Pirinç kabuğu, buğday sapı ve talaşın karışımdaki kütlesel yüzdesi arttıkça karışımın minimum akışkanlaşma hızı artmaktayken zeytin posası ve fındık kabuğunun karışımdaki kütlesel yüzdesindeki değişimlerin minimum akışkanlaşma hızı üzerinde herhangi bir etkisi olmamıştır. Karışımdaki silis kumunun parçacık büyüklüğündeki artış, aynı biyokütle kütlesel yüzdesine sahip karışımların minimum akışkanlaşma hızında artışa neden olmuştur. Bütün biyokütle-silis kumu karışımları için kararlı rejim durumundaki yataktaki dikey karışım örüntüsü benzer bulunmuştur. Biyokütle parçacıklarının daha düşük özkütleye sahip olmalarından dolayı, akışkanlaşma sırasında, biyokütle parçacıkları yatağın üstünde, silis kumu ise yatağın alt kısmında birikmiştir. 2-boyutlu yatak deneyleri, biyokütle parçacıklarının silis kumuyla karıştırılmasının yatakta arzu edilen kabarcık davranışını sağladığını göstermiştir.

Anahtar Kelimeler: Akışkan yatak, hidrodinamik, biyokütle.

To My Parents

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I wish to express my deepest gratitude and appreciation to my supervisor Prof. Dr. Hüseyin Vural and my co-supervisor Assoc. Prof. Dr. Murat KÖKSAL who inspired, encouraged and supported me throughout of this study.

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LIST OF SYMBOLS AND ABBREVIATIONS

u_{mf}	Superficial velocity of gas at minimum fluidization, m/s
u_s	Minimum fluidization velocity of smaller component in single component fluidized beds, m/s
u_b	Minimum fluidization velocity of larger component in single component fluidized beds, m/s
x_b	Mass fraction of larger particle in a binary mixture
u_f	Minimum fluidization velocity of fluid component in single component fluidized beds, m/s
$\bar{\rho}$	Skeletal density (excluding particle pore volume), kg/m^3
$\bar{d}$	Mean particle size in a binary system based on volume fractions, m
ρ_f	Particle density of fluid component in binary mixture, kg/m^3
d_f	Particle size of fluid component, m
u_{pk}	Minimum fluidization velocity of packed bed component in single component fluidized beds, m/s
x_f	Weight fraction of fluid component in binary mixture
$\mathrm{Re}_{p,mf}$	Particle Reynolds number at minimum fluidization

$\bar{d}_p$	Mean particle size in a binary system based on mass fractions, m
ρ_g	Density of gas stream, kg/m^3
μ	Viscosity of gas stream, kg/ms
u_{vf}	Superficial velocity of gas where both components in a binary mixture are fluidized, m/s
X_f	Real volume fraction of fluid component
d_{peff}	Effective diameter of the mixture, m
ρ_{eff}	Effective density of the mixture, kg/m^3
g	Acceleration due to gravity, m/s^2
x_{local}	Local mass percentage
$x_{overall}$	Overall mass percentage
Mtoe	Million tons of oil equivalent
Ktoe	Kilo tons of oil equivalent
MF	Minimum fluidization
MX	Mixing

FC	Fluidization characteristics
MI	Mixing index

CHAPTER 1

INTRODUCTION

Biomass is standing as an important source of renewable energy and efficient utilization of it contributes energy sustainability of the world. Biomass energy potential of Turkey and world and efficient energy conversion processes are noteworthy factors to be taken into consideration. This chapter aims to give brief information about biomass as being an energy source and appropriate energy conversion techniques for it.

1.1 Biomass and Its Importance

Biomass is the name used to describe organic materials obtained from plants and animals. Wood, agricultural yields and their residues, animal and municipal solid wastes and wastes from food production are all called biomass. Since they carry carbon within their constitutions, they serve as energy sources. Biomass is the known oldest form of energy used by human being.

Wheat straw, barley straw, hazelnut shell, rise husk, maize stalk, cotton cocoon shell, sunflower shell are typical agricultural residues that can be considered as biomass. Olive cake, tea waste, fruit waste are some examples of wastes that are obtained from food processing. Sugar cane, sugar beet and sweet sorghum are called modern biomass and they are grown as an energy crop for their significant energy potential.

Energy demand is growing parallel to the technological development and industrialization. Consuming fossil fuels to supply required energy causes significant environmental problems such as global warming. Limited sources of fossil fuels are thought to become exhausted in about fifty years. Global environmental problems together with limited amount of fossil fuels place pressure on the governments to take some precautions. Renewable energy arises as an alternative solution for the future energy crisis. Efficient use of renewable energy sources decreases the dependency to the fossil fuels, leading to sustainable and environmentally friendly energy supply.

Use of biomass as an energy source begins with the discovery of fire. Biomass energy has no effect on the world's carbon cycle since the process photosynthesis requires carbon during the formation of biomass. This absorbed carbon is again released to the atmosphere when biomass is burned. Cycle starts with sprout of plants and ends with burning of these plantations. Biomass energy has an essential potential within renewables and it is predicted to become one of the major energy sources in the future. Different scenarios have been suggested about the contribution of biomass energy to the future energy supply of the world. Most of the scenarios come up with the increase of share of biomass energy. These predictions point out the importance of biomass energy.

1.2 Biomass Energy in World

Energy has become the major driving force behind the modern world and demand for it is continuously increasing. To meet increasing energy demand, fossil fuel sources are used and this brings about new problems such as global warming or depletion of these sources. Sustainable energy polices are executed by governments to cope with energy related problems. Renewable energy is sustainable and environmental friendly. Wind, solar, biomass, hydro, geothermal, ebb and flow are all renewable energy sources and have different shares in the total energy production of the world.

Biomass energy has been used for centuries by human being and it constitutes an important part of world's energy supply. Especially in the developing countries, biomass energy has crucial importance. It is used for domestic heating and cooking in the rural areas. In urban areas, addition to domestic heating it is used to supply process heat in industry and used to produce electricity. The share of total primary energy supply of the world in 2005 is given in Figure 1.1 and as indicated, biomass energy has share of 10.0%. About 80% of the total primary energy is supplied from fossil based fuels.

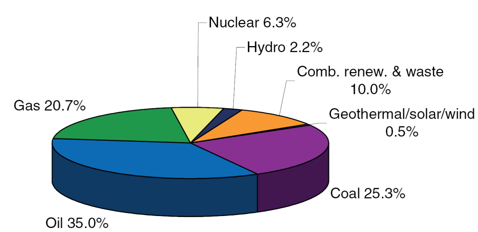


Figure 1.1 Share of World Total Primary Energy Supply in 2005, [1]

The total primary energy supply of the world from 1971 to 2005 is given in Figure 1.2. The shares of different energy sources in the total energy production can also be seen from the diagram. Total energy production was doubled in this period. Energy from biomass increased also and it had the highest share within all renewable energy sources.

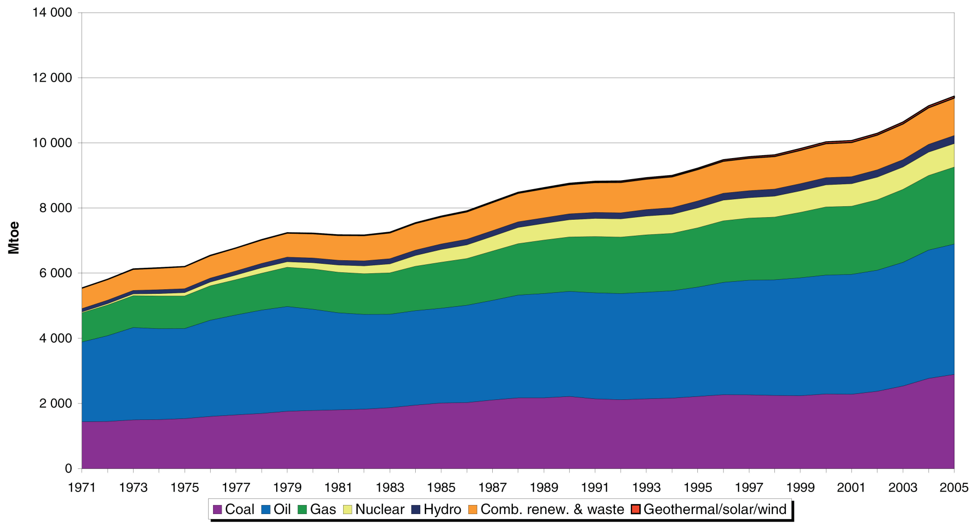


Figure 1.2 Evolution of Total Primary Energy Supply of World from 1971 to 2005 [1]

Biomass is predicted to meet important part of the energy demand in the next century. However it is currently utilized widely in developing countries, in the future, industrialized countries will also take some actions to establish modern bioenergy plantations as sustainable energy systems. Many studies have been undertaken to assess the possible contribution of biomass to the future global energy supply. Figure 1.3 shows the scenarios of different researchers that predict the potential biomass supply for energy over time. These studies have arrived at widely different conclusions about the possible contribution of biomass in the future global energy supply (e.g., from below 100 EJ yr-1 to above 400 EJ yr-1 in 2050). The major reason for the differences is that the two most crucial parameters-land availability and yield levels in energy crop production - are very uncertain, and subject to widely different opinions (e.g., the assessed 2050 plantation supply ranges from below 50 EJ yr-1 to almost 240 EJ yr-1) [2]. Both total primary energy supply and bioenergy share of the total energy supply are expected to increase in this century.

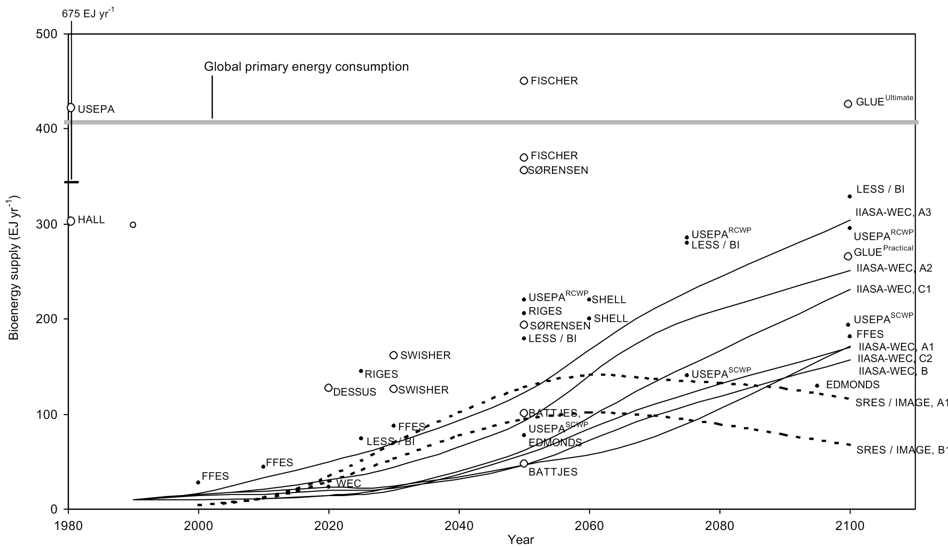


Figure 1.3 Potential Biomass Supply for Energy over Time. Resource-focused studies are represented by hollow circles and demand-driven studies are represented by filled circles [2]

1.3 Biomass Energy in Turkey

Turkey is located in the northern hemisphere between the 36°-42° northern parallel and 26°-45° eastern meridian. It has a population of 70 million and has an area of 783,562 km^2. Turkey is a developing country and industrialization together with technological developments increases the energy demand of the country. The estimated energy necessity of Turkey is given in Figure 1.4. In 2010, the energy consumption in the country expected to reach about 160 Mtoe.

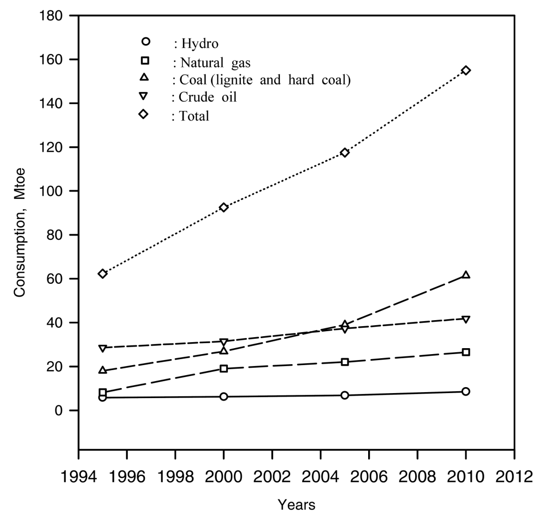


Figure 1.4 Turkey's Primary Energy Necessity (1995-2010) [3]

Petroleum and natural gas resources are very limited in Turkey and it imports almost all petroleum and natural gas which leads to energy dependency to other countries. This reveals the fact that new energy source should be introduced to avoid energy dependency. Renewable energy seems to be the most probable choice considering the available energy sources. Efficient use of renewable energy potentials lessens the energy import, provides economic growth and decreases the air pollution.

Renewable energy sources are mainly hydro, biomass, wind, solar and geothermal and they have different shares within total energy production and total energy supply of Turkey. Their shares in the total primary energy supply in the year 2005 are given in Figure 1.5. As can be inferred from the figure, biomass and hydro are the two main renewable energy sources that are utilized currently with the shares of 6.3% and 4.0% respectively. Geothermal, solar and wind energies constitutes the 1.6% of the total energy supply.

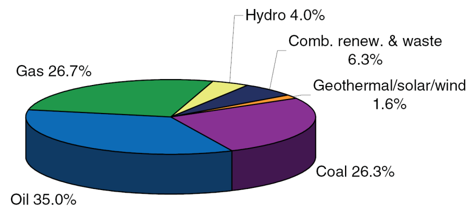


Figure 1.5 Share of Total Primary Energy Supply of Turkey in 2005 (85 Mtoe) [1]

In Figure 1.6, evolution of total primary energy supply of Turkey from 1971 to 2005 is shown. It was increased from 20 Mtoe to about 85 Mtoe within this period. Energy from gas, especially from natural gas was started to be supplied from 1987 and its share grew rapidly. Coal and oil were utilized with increasing amount as parallel to the energy demand.

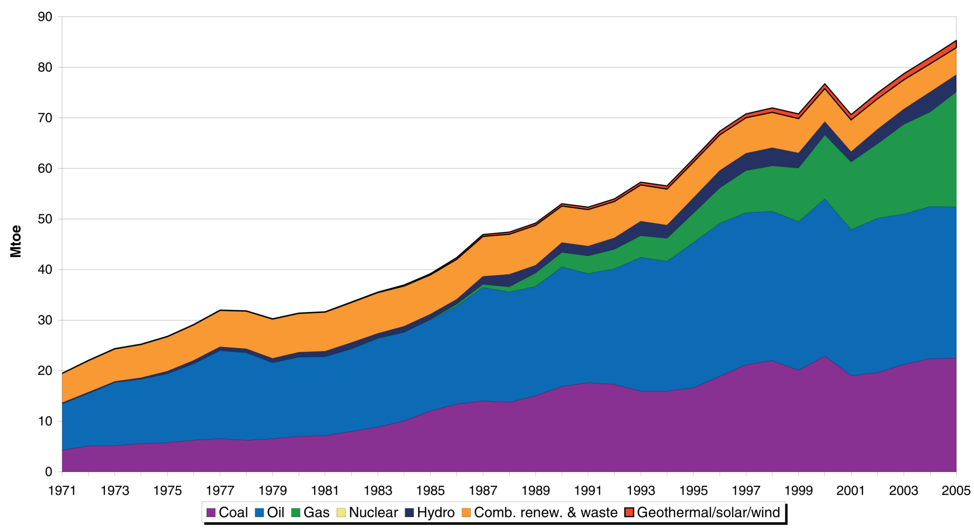


Figure 1.6 Evolution of Total Primary Energy Supply of Turkey from 1971 to 2005 [1]

In Turkey, bioenergy especially has important role as a major energy supply in the rural areas. It is used for heating homes, cooking and cleaning activities. Domestic energy consumption accounts for 37% of the total energy consumption. Of this, about 52% are biomass-based fuels [4].

Wheat straw, rice husk and hazelnut shell are employed in this study as biomass materials and they are all agricultural residues. Table 6 shows the Turkey's agricultural residue potential in 2001. As wheat and barley are the most abundant agricultural products in Turkey, their residues stands in the first two ranks in agricultural residues.

Table 1.1 Turkey's agricultural residue potential in 2001, [5]

Agricultural residue	Annual production (million tons)	Energy potential (Mtoe)
Wheat straw	26.4	7.2
Barley straw	13.5	3.9
Maize stalk	4.2	1.2
Cotton cocoon shell	2.9	0.9
Sunflower shell	2.7	0.8
Sugar beet waste	2.3	0.7
Hazelnut shell	0.8	0.3
Oat straw	0.5	0.2
Rye straw	0.4	0.1
Rice husk	0.4	0.1
Fruit shell	0.3	0.1
Total	54.4	15.5

1.4 Energy from Biomass

Biomass is formed as a result of the process photosynthesis which converts light energy of sun to chemical bond energy that is stored within biomass structure. Photosynthesis is the reaction between CO_2, water and sunlight to produce carbonhydrates that constitute basic units of biomass. Energy is stored within these carbonhydrates as chemical bond energy. If biomass is subjected to any bio-chemical or thermo-chemical process, the stored chemical energy is released as heat or converted to another form such as bio-gas.

Use of wood or other forms of biomass as fuels to generate electricity and heat has become a focus of renewed interest in many parts of the world. Biomass is an indigenous, often cheap and above all renewable fuel. This increasing availability of biomass, combined with the recent development of technologies to use it efficiently and with low levels of emissions, promise to make biomass an increasingly attractive fuel option [6].

Using biomass as a fuel eliminates the dispose problem of environmentally detrimental resources (such as municipal solid waste and agricultural residues).

Chemical and physical properties of biomass materials determine their suitability as a fuel for bio-chemical or thermo-chemical processes. The most important properties relating to the thermal conversion of biomass are as follows:

- Moisture content
- Ash content
- Volatile matter content
- Elemental composition
- Heating value
- Bulk density

1.5 Biomass Energy Conversion Processes in Fluidized Bed

Biomass can be converted into two energy related product, namely heat/power generation and engine fuel. It can also be converted to some other type of product to be used as a chemical feedstock. Energy conversion process depends heavily on the biomass' chemical and physical properties, end-use required energy form and environmental-economical considerations.

Conversion can be achieved through mainly two routes, one is thermo-chemical processes and the other is bio-chemical processes.

1.5.1 Thermo-Chemical Conversion Processes

Within thermo-chemical conversion, three process options are mostly utilized; combustion, pyrolysis, gasification. These processes can be achieved successfully for biomass materials in fluidized beds.

1.5.1.1 Combustion

Combustion of biomass is the oldest type of energy conversion process of biomass dated to the discovery of fire and it is described as the burning of biomass in air. As a result of combustion process, hot combustion products (gases) are released.

Fixed-bed and fluidized-bed systems arise as the two combustion systems, each having different pros and cons. In a fixed-bed combustion system, fuel is burned above a grate. Primary and secondary air is supplied for the combustion of solid char in the bed and the volatile matter combustion above the bed. Typical operating temperature of such combustor is between 850 and 1400 °C.

Fluidized-bed system consist of bed of particles of sand, limestone or another non-combustible particle with fuel staying on a distributor plate that distributes the air uniformly to the bed and air flow to provide particle suspension in the bed. The bed of particles (sand, limestone etc.) behaves like a heat transfer medium. The operating temperature of a fluidized-bed combustor varies between 700 and 1000 °C. This relatively lower operating temperature provides lower NO_x emissions and prevents ash melting.

1.5.1.2 Gasification

Gasification is the production of combustible gases by partial oxidation of a fuel (coal, petroleum based materials, biomass etc.). The gas released by gasification process is called syngas. It is composed of mainly hydrogen and carbon monoxide that can be used as a fuel or as a chemical feedstock. Gasification medium may be air, steam, oxygen or hydrogen.

Gasification units can be classified into two types; fixed-bed gasifiers and fluidized-bed gasifiers. Fixed-bed gasifiers divided into three types with respect to the direction of fluid flow; updraft or countercurrent gasifiers, downdraft or cocurrent gasifiers and cross-draft gasifiers. Explosions, fuel blockages, corrosion and tar production are the main problems of fixed-bed gasifiers. Fluidized-bed gasifiers involves sand or other suitable non-combustible particles as a bed material mixed with fuel and fluid flow to suspend these particles in the bed. Their relatively low operating temperatures (750-900 °C, in fixed-beds 1200-1500 °C) provide low tar conversion rates.

1.5.1.3 Pyrolysis

Pyrolysis is the chemical decomposition of an organic material in the absence of air at relatively high temperatures. Organic materials are converted into gases, liquids in small quantity and solid residue containing carbon and ash. If biomass is heated to about 750 K in the absence of air, bio-oil (or bio-crude), charcoal and non-combustible gases, acetic acid, acetone and methanol are obtained as products of pyrolysis. This technology is used for refining crude fossil fuel oil and coal [9].

1.6 Organization of the Thesis

This study consists of totally six chapters. Their contents are given briefly below.

In Chapter-2, literature review about minimum fluidization velocity and mixing/segregation behavior of biomass-sand mixtures are given. Necessity of this study is mentioned referring to the gaps in the literature that are aimed to be filled by this study.

In Chapter-3, some fundamental issues related to fluidized beds is presented briefly. The phenomenon of fluidization, history, application fields, advantages, disadvantages and types of fluidized beds and hydrodynamics occurring in bubbling fluidized bed having biomass-sand binary mixture as an inert material is expressed.

In Chapter-4, information on experimental set-up, equipment and methodology is presented. Biomass materials used in this work and some of their physical and chemical properties, experimental set-up, procedure and matrix of experiments conducted are given.

Chapter-5 includes the results and discussions of the experiments. First part of this chapter gives the minimum fluidization velocities of biomass-sand mixtures determined by experiments and comparison of the results with the correlations available in literature. Part-2 gives the mixing/segregation occurring in the bed of biomass-sand mixtures and discusses about their mixing quality. Part-3 can be perceived as a visual tool to investigate the fluidization and bubble behavior of biomass and biomass-sand mixtures in a two dimensional fluidized bed.

In Chapter-6, general conclusions and recommendations for future work are presented.

CHAPTER 2

LITERATURE REVIEW

Literature review about hydrodynamic behavior of biomass materials and binary mixtures of biomass-silica sand is presented in this chapter. Studies related to minimum fluidization velocity and mixing/segregation behavior of binary mixtures of biomass and sand is reviewed and the gaps filled by this work are mentioned.

2.1 Minimum Fluidization Velocity for Binary Mixtures of Biomass and Silica Sand

Biomass-agricultural and forest residues and sometimes certain urban and industrial wastes can be processed thermochemically in order to yield gases, tars and a carbonaceous residue (char) which can be employed for energy purposes. Among the well-known thermochemical processes are gasification, pyrolysis, combustion or incineration in fluidized beds (bubbling, fast, circulating and circulating-multisolid beds) Pilar et al. [19,20].

It generally appears to be assumed that the design and operation of equipment involving biomass materials can be based on conventional fluidization knowledge and methodologies. However, the properties of biomass particles are sufficiently unique that the importance of the fluidization behavior of biomass particles is under-estimated. In particular, there is very little knowledge of how fluidized bed hydrodynamics and related properties are affected by such characteristics as extreme particle sizes and shapes, moisture content and compressibility. Since the hydrodynamics are critical to successful design and operation of fluidized bed processes, it is important to undertake research directed at improving the characterization and modeling of biomass fluidization hydrodynamics [21].

Two guiding studies were conducted about minimum fluidization velocity of binary mixtures by Cheung et al. in 1976 and Chiba et al. in 1979.

Cheung et al. [13] used binary mixture consisting of small and large particles each having roughly equal sized particles for fluidization experiments. They performed a series of experiments to determine the change in minimum fluidization velocity with different compositions of small and large particles. As a result, they obtained a correlation predicting the minimum fluidization velocity of binary mixtures consisting of small and large particles. This correlation based on components' minimum fluidization velocities and mass fraction of large particles in the mixture.

Chiba et al. [14] showed that, U_{mf} which is a simple concept and simple to measure in a mono-component fluidized bed, is complex in both definition and measurement for any binary system. They conducted experiments by using binary mixtures of copper shot, copper powder, glass beads, hollow char and silica balloons which have spherical shape and vary in their size and density. They derived equations for predicting the change of U_{mf} for cases of total segregation and complete mixing of the two components. The equations are based on components' densities, sizes, weight fractions and minimum fluidization velocities.

Although studies of Cheung et al. [13] and Chiba et al. [14] do not include biomass particles, they guide to the researches on minimum fluidization velocity of binary mixtures of biomass and an inert material. Few researchers performed studies related to binary mixtures of different biomass materials and inert particles to determine their minimum fluidization velocities.

Noda et al. [11] studied experimentally the minimum fluidization velocity of binary mixtures that are composed of particles with large size and density ratio. Particles of different shapes such as wood chips, rubber sheets, glass beads, iron beads, soya beans and small beans were used as coarse particles and nearly spherical fine particles of sands and glass beads were used as a fluidized medium. They have developed correlations to predict the true minimum fluidization velocity of binary mixtures for completely and partially mixed beds by modification of the equation of Wen and Yu. They argued that, minimum fluidization velocity of binary mixtures depend on the mixing behavior of the bed and volume fractions of fluidizing media.

Bibao et al. [15] determined the minimum fluidization velocities for sand-wheat straw binary mixtures for different experimental conditions. The velocity values obtained have been correlated with the straw and sand sizes and the proportions of both solids in the bed. They also determined the maximum amount of wheat straw in the mixture that can be fluidized in different conditions. They argued that the proposed equations were unable to predict the minimum fluidization velocities of mixtures used in their work due to the following reasons: 1.) Mixture with more than 15% weight fraction of wheat straw does not fluidize and equations based on weight fraction is thought unusable. 2.) Minimum fluidization velocity of wheat straw can not be determined since it does not fluidize on its own and equations including this term can not be used.

Pilar et al. [19, 20] investigated the fluidization of mixtures of biomass with a second solid by two parts. Definitions of the minimum fluidization and maximum fluidization velocities for these mixtures are discussed in this first part. Second part presents experimental data on fluidization of biomass and a second solid. Cereal straw of three different sizes, pine thinnings, sawdust, woodchips of various sizes and ground thistle from energy plantations were the biomass materials that were used in their study. The second solids employed in these mixtures were beach and silica sands of different sizes and densities, dolomite and a commercial catalytic cracker. Minimum fluidization velocities were determined in columns of 14 and 30 cm in diameter. They argued that no proposed equation was able to predict all the results of their study.

Rao et al. [16] studied on fluidization of mixtures of biomass and sands. The biomass materials used are rise husk, sawdust and groundnut shell powder and the sands employed are of two different densities and particle sizes. A 5 cm ID fluidized bed column was used to determine the minimum fluidization velocities of the mixtures. The percentages of biomass materials in the mixtures were 2, 5, 10 and 15% by weight. Equations were developed for predicting the U_{mf} values of these mixtures. The equations were also tested for their validity against the data in current literature on U_{mf} values of mixtures of biomass and sands and also mixtures of particles of different sizes only. Their equations predict the minimum fluidization velocities of binary mixtures of particles with different densities and sizes well. It is also found that the equations satisfactorily predict the minimum fluidization velocities for mixtures of particles of same density but different sizes.

Abdullah et al. [22] conducted a systematic theoretical and experimental study to obtain hydrodynamic properties such as particle size diameter, bulk density, fluidizing velocity, etc. for locally available biomass residue fuels in Malaysia like rise husk, sawdust, peanut shell, coconut shell, palm fiber as well as coal and bottom ash. They used a laboratory scale fluidized bed to perform their experiment. Measured bed-pressure drop against superficial air velocity data used to obtain minimum fluidization velocity for each individual particle type at different bed heights. Bulk density and voidage were found as the main factors contributing to fluidizing quality of the bed. They noted that larger bulk density materials have better fluidization quality and voidage gives adverse effect to fluidization.

Patil et al. [23] researched on fluidized-bed gasifier as a means to gasify feedstock in a process to produce ethanol from biomass. Fluidization characteristics of the bed, especially minimum and complete fluidization velocities were determined since they are critical for the operation of the gasifier. Experiments were conducted to determine fluidization behaviors of sand-switchgrass mixtures with different particle sizes and bulk densities. A 250 mm ID transparent fluidized bed column having same dimensions with laboratory scale gasifier was utilized. The percentages of chopped switchgrass in the mixtures were 1.0, 2.0, 2.9, 4.8, 6.5 and 8.3% by weight. Sand particle sizes studied had geometric mean diameters of 375, 381, 450, 621 and 863 μm. They found that minimum and complete fluidization velocity values were more sensitive to the sand particle size than to the percent switchgrass level in the switchgrass-sand mixtures. Slugging occurred at the higher levels (above 4.8%) of switchgrass in chopped switchgrass-sand mixtures and they suggested a practical upper limit of switchgrass of less than 5% of the overall bed mass.

Clarke et al. [24] investigated the fluidization behavior of binary mixtures of moist sawdust and glass spheres. Since the sawdust alone was observed to fluidize poorly, with extensive channeling occurring, 0.322 and 0.516 mm glass spheres were added to the bed of sawdust to improve the fluidization characteristics. Complete mixing was achieved for mixture of sawdust and 0.322 mm sphere whereas partially or complete mixing occurred for mixture of sawdust and 0.516 mm spheres depending on the gas velocity. Moisture content increase created resistance for fluidization since it contributed to interparticle liquid bridging forces and lead to increase in minimum fluidization velocity. They determined an upper limit of moisture content of sawdust at which fluidization can be achieved. They also argued that existing correlations are unsuccessful at predicting the minimum fluidization velocity of the binary mixtures of glass spheres and sawdust due to the following reasons: The correlations of Noda et al. (1986) and Bilbao et al. (1987) are based on different definitions of minimum fluidization velocity. In addition, the correlations of Cheung et al. (1976), Noda et al. (1986), Bilbao et al. (1987), and Chiba et al. (1979) may be strongly dependent on the types of particles used in their experiments.

Grace et al. [21] presented an overview of research reported on gas flow and particle motion in fluidization processes involving biomass particles, as well as recommendations for future work. They emphasize on necessity for the following research areas related to fluidization of biomass particles:

• To test fluidization hydrodynamic characteristic for wide ranges of biomass particles, and compare the results with those for more conventional particles.

• To understand the influence of key particle properties (e.g. particle size distribution) and the presence of particles of extreme shapes (e.g. long thin stalks or flat chips), so that biomass particles can be tailored to provide improved performance.

• To evaluate fluidization quality and optimize gas-solid flow. Among the topics requiring attention are mixing of binary (biomass and inert) particles, radial and axial species concentration profiles.

• To provide criteria for the specification optimum inert particles when these are needed to fluidize biomass particles.

• To study the effect of temperature on the motion of biomass particles in fluidized beds.

• To develop novel and effective configurations to optimize the conditions for biomass particles, with favorable gas-solid mixing and contact efficiencies.

• To develop multiphase flow models, combining elements from experimental findings, conventional models and more advanced techniques like CFD to quide design and operation of biomass processes.

2.2 Mixing and Segregation of Binary Mixtures of Biomass and Silica Sand in a Bubbling Fluidized Bed

Mixing and segregation of components composing the binary mixtures is crucial for the design and operation of fluidized bed and many researchers conducted studies focusing on this subject. These studies mainly treated the binary mixture of particles having different shape, size and density but studies for biomass and sand mixtures are very limited. Axial and radial distribution of biomass particles during operation of a fluidized bed gasifier or combustor is critical to get better performance. If segregation occurs in the bed, formations of hot spots are very possible and this adversely affects the bed operation.

There are many experimental and computational studies about mixing and segregation of particles having different sizes, shapes and densities but studies related to the mixing and segregation behavior of biomass-sand mixtures in fluidized bed are very limited in the literature.

Shen et al. [25] conducted an experimental study to investigate the biomass mixing in the bubbling fluidized bed gasifier. They developed a digital image processing based technique in their paper. The experiments were performed in a cod model of bubbling fluidized bed with a rectangular cross-section of 40x400 mm^2 and a height of 1400 mm. Red wooden particles were used as tracer particles. Red wooden particles contained in a 50 mm ID soft, plastic tube were injected into the bed in about 0.2 s at splash zone level during steady state operation. The bed was uniformly illuminated by 2x1500 W light bulbs. The biomass mixing was captured using a CCD digital video camera. With the combination of image processing and wavelet analysis, R-G-B images taken by a digital video camera are used to detect the distribution of tracer particles and to determine the continuous variation of biomass concentration profiles in a fluidized bed. They reached the following conclusions: (a) biomass mixing is provided by movement, interaction, coalescence of bubbles together with bursting of bubbles at the bed surface, (b) vertical mixing rate was found to be higher than lateral mixing due to larger vertical convection, (c) increase in superficial gas velocity resulted in decrease of biomass concentration at the bottom region, (d) mixing determined to be more uniform at lower superficial gas velocities, (e) increase in superficial gas velocity lead to movement of biomass particles from wall to center of the bed leading more uniform lateral concentration of biomass.

Qiaoqun et al. [26] studied experimentally and theoretically the fluidization behavior rice husk-sand mixture in the gas bubbling fluidized bed. Experiments were performed in a cold model fluidized bed having dimensions 245x450x2000 mm. A computational fluid dynamic model has been presented where the kinetic theory of granular flow forms the basis for the turbulence modeling of the solid classes. They discussed the definition of minimum fluidization velocity by concerning the pressure drop-superficial gas velocity profile and determined minimum fluidization velocity for the mixture. They tried to investigate the effects of particle physical properties and operative conditions on the fluidization and mixing behavior or the biomass-sand mixture. According to their findings, superficial gas velocity together with diameter and density of jetsam particles has significant effect on fluidization behavior. Mass fraction increase caused increase in minimum fluidization velocity. Results of simulation indicate the particle size, mass fraction of sand particles and superficial gas velocity has considerable impacted on the segregating behavior of rice husk particles. The simulated results are in agreement with measured mass fraction of rice husk particles.

2.3 Objectives of the Study

As mentioned above, literature about hydrodynamics especially for mixing/segregation behavior of biomass-sand mixtures is very limited and research focusing on these issues is a big necessity. There is no study carried out for hydrodynamic behavior of olive cake and hazelnut shell in a bubbling fluidized bed in the literature. These two biomass materials are important for Turkey and researches for their efficient utilization for energy production make great contribution to energy sustainability of the country. Gaps related to biomass fluidization that are intended to be filled by this study are listed below;

- To determine the effects of biomass mass fraction and inert particle size on minimum fluidization velocity of different biomass-inert particle binary mixtures.

- To compare the results of the experiments with the predictions of available correlations estimating minimum fluidization velocity of binary mixtures and discussing their performance.

- To determine mixing/segregation behavior of biomass-inert particle binary mixtures having different mass fractions of biomass and different sand particle sizes.

- To present fluidization and bubbling behavior of pure biomass materials and biomass-inert particle binary mixtures by images taken from a two dimensional fluidized bed during steady state operation as a visual tool.

2.4 Scope of the Study

This study includes the experimental analysis of biomass-sand mixtures in laboratory scale cold model fluidized beds. Experimental works consist of three parts. First part covers the determination of minimum fluidization velocities of mixtures of biomass-sand in a plexiglass bed having 14.6 cm ID. Effects of biomass mass fraction and sand particle size on minimum fluidization velocity of mixtures is investigated. Second part intends to find out the mixing/segregation behavior of biomass-sand mixtures in the same bed used for experiments of first part. Changes in mixing pattern for different particle size of sand and mass fraction of biomass are determined. In the third part, a two dimensional plexiglass fluidized bed column with dimensions of 15 mm width, 490 mm length and 1200 mm height is utilized to investigate the fluidization and bubbling characteristics of biomass-sand mixtures. For different mass fractions of biomass materials, fluidization and bubbling behaviors of mixtures are observed at different superficial gas velocities.

CHAPTER 3

FLUIDIZED BED FUNDAMENTALS

The objective of this chapter is to present some fundamental aspects of fluidized beds. After giving brief information about fluidization and fluidized beds, hydrodynamics occurring in a bubbling fluidized bed of binary mixtures, especially binary mixtures of biomass-silica sand is mentioned. Available correlations proposed for predicting the minimum fluidization velocity of binary mixtures and mixing/segregation mechanisms of binary mixtures in fluidized bed are presented.

3.1 The Phenomenon of Fluidization

Fluidization is the suspension of solid particles as a result of frictional forces exerted by the fluidizing medium that flows through bed of particles in the upward direction. When the force exerted by the fluidizing medium is equal to the weight of the bed material, the bed becomes fluidized and the velocity at that point is called minimum fluidization velocity. Fluidizing medium can be either gas or liquid depending on the application requirements. Behind the minimum fluidization velocity, the bed exhibits fluid-like behavior resulting in advantages in many applications. They are namely; surface of the solid particles stays horizontal even bed is inclined, if there is a link between two fluidized bed their heights becomes equal, solid particles spurt out through a hole in the bed wall, lower density materials float whereas higher density materials sink etc.

The behavior of particulate solids in fluidized and aerated systems depends largely on a combination of their mean particle size and density, and is usually discussed in terms of the Geldart fluidization diagram as shown in Figure 3.1. This relate to powders fluidized by air at ambient conditions and can be used to place any given powder in one of the four groups A, B, C or D. Powders within any group have similar fluidization characteristics [9].

Powders in group A have the most desirable fluidization properties. They expand significantly when fluidized, and take a long time to de-aerate after the gas supply is cut off. Interparticle forces are present in group A powders, but are smaller than the hydrodynamic forces. Gas bubbles are limited in size and may break up at high fluidizing velocities. In group B and D there are no interparticle forces. Bubbles grow indefinitely with bed depth and gas velocity, being limited only by the size of the column [9].

Group C powders in Geldart's classification consist of cohesive fine particles. Interparticle forces existing between Group C particles lead to some fluidization problems. Crack and channel formation instead of bubbling bed is a characteristic behavior of this particle group.

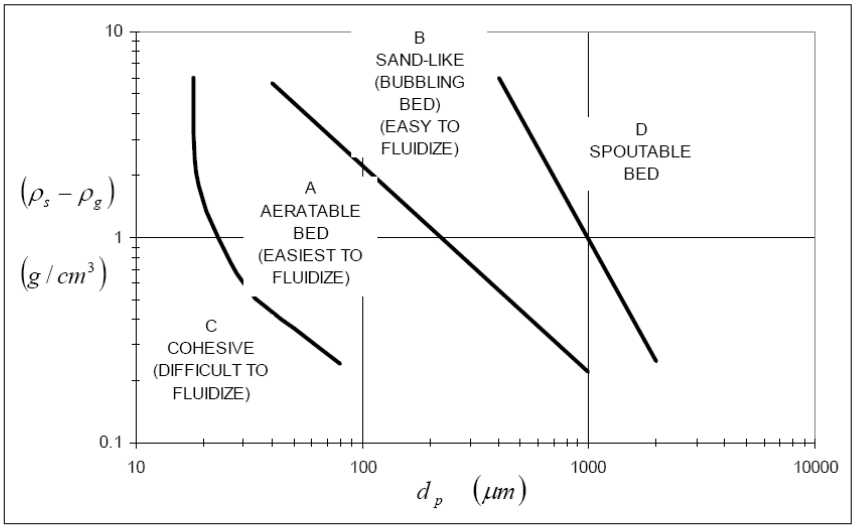


Figure 3.1 Geldart's Classification of Particles

3.2 A Brief History and Application Fields of Fluidized Bed Technology

Fluidized bed technology firstly appeared in 1922 as a coal gasifier. During the World War-II it was widely utilized to obtain high octane petroleum. At the end of 1970s, this technology was made use of coal combustion due to its ability to combust coal in an environmentally friendly manner. Today, fluidized bed technology is being utilized for a wide range of industrial applications. Some of the application fields of fluidized bed technology are gasification of coal, fluid catalytic cracking (FCC), transportation-classification or mixing of particles, plastic coating, drying and ore roasting.

3.3 Advantages and Disadvantages of Fluidized Beds

3.3.1 Advantages

- Perfect mixing of bed material that leading to uniform temperature distribution in the bed.

- Low bed temperature relative to the conventional combustors and as a result, low NO_x formation, no ash fusion and low corrosion in the bed.
- Eliminating necessity to expensive scrubber systems by keeping SO_x in the bed by using limestone as a bed inert material.
- Higher heat transfer coefficient inside the bed than conventional coal combustors which provide smaller size combustion units and lower installation cost.
- Ability to combust low quality fuels (fuels with high ash, sulphur, moisture content and low calorific value).

3.3.2 Disadvantages

- Fan power consumption to supply fluidizing air into the bed.
- Despite of the good mixing provided by bubbles, air carried by bubbles can leave the bed without reacting and this cause combustion process with more excess air.
- Erosion of heat transfer surfaces.
- High flow rate of gas may reduce the combustion efficiency by elutriating particles from the bed.
- Need for effective cyclone system to prevent elutriation of fuel particles and to increase combustion efficiency.
- Scale up problems.

Fluidized bed technology has been used for many industrial operations in the last decade which prove its success.

3.4 Types of Fluidized Beds

3.4.1 Bubbling Fluidized Bed

When there is a gas flow through bed of solid particles in the upward direction, gas passes through voids between particles and if the velocity of the gas is low, no motion occurs in the bed and this case is called fixed bed. If the gas velocity is increased, void between particles increases also but no significant motion is observed and this case is called expanded bed. Further increase in gas velocity lead to suspension of the particles in the bed and this situation is called fluidization state. When the superficial gas velocity exceeds the minimum fluidization velocity, bubble formation is observed in the bed which gives the name to that kind of beds. Bubble formation is observed in the bed behind minimum fluidization velocity. Bubble formation starts at the surface of distributor plate and their coalescence leads to increase in their size and velocity as they rise along the bed. That inherent mechanism of bubbling beds is the driving force for mixing of the bed material that provides uniform temperature distribution in the bed for thermochemical operations. Bubbling fluidized beds operate at atmospheric pressure and they are widely utilized in thermochemical processes such as combustion and gasification. Bubbles have many positive effects on the bed operation such as providing circulation of bed material that leads to uniform mixing and temperature distribution throughout the bed. Design of distributor plate is very crucial in these types of fluidized beds. Wrong design may result in formation of big bubbles that negatively effects the bed operations such as leaving of gas carried by bubbles without reacting with fuel causing lower combustion efficiency.

3.4.2 Circulating Fluidized Bed

In these types of fluidized beds, solid particles are carried through the bed with high velocity fluidizing gas and return to the bed after separated from the gas by cyclones.

Velocity of the fluidizing gas is higher than the terminal velocity of the particles to provide circulation. Emulsion and free board zone can not be detected since all the bed material is circulated. High efficiency cyclones enable the return of the particles to the bed column. Horizontal heat transfer pipes are not employed due to erosion problems. Limestone particles used in circulating fluidized bed combustors consist of fine particles effecting the SO_x limestone reaction in the positive way and providing less SO_x release to the atmosphere. This is the most important advantage of the circulating fluidized beds.

3.4.3 Pressurized Fluidized Bed

Bubbling and circulating fluidized beds operates under atmospheric pressure conditions whereas pressurized fluidized beds operate at pressures around 5-20 bar. Energy contained in the gas leaving the bed at high pressures can be converter to utilizable energy by gas turbines. Cyclones used in pressured fluidized bed have noteworthy role due to damage risk of turbine blades by solid particles contained in the gas flow. Energy production density is higher than other two types of fluidized bed. SO_x capture can be well achieved. Bed materials used in pressured fluidized bed have to withstand high pressures.

3.5 Fluidization Regimes in Bubbling Fluidized Bed

In bubbling fluidized beds, solid particles are situated on a distributor plate and surrounded by bed walls. Fluidizing gas is injected into the bed through distributor plate in the upward direction, passes through voids exist between solid particles and leaves the bed. Friction effects between gas and particles cause pressure drop for the gas. Pressure drop increases linearly with increase in gas velocity up to some point. At that point the solid particles do not sense the weight of the above ones, in other words the friction force counterbalance the weight of the particles. This point is called incipient (or minimum) fluidization point and the gas velocity at that point is called minimum fluidization velocity. If velocity is increased a little further, particles depart from each other, bed expands uniformly. This case is called uniform fluidization. This type of fluidization regime is encountered in liquid fluidized beds at low velocities. In gas-solid fluidized bed, beyond minimum fluidization velocity bubble formations starts. In spite of low bed expansion, well mixing conditions occur in the bed. This situation is called bubbling fluidization. Channels may form in the bed due to bed particles' physical properties or mistakes in the design of distributor plate. This is called channeling. Increase in gas velocity lead to coalescence and increase in bubble size and this may creates bubbles having same size with bed. In such a situation particles and bubbles forms layers and aggregative particle movement occur in the bed. This case is called slugging bed. At higher gas velocities, velocity of gas may exceed the terminal velocity of particles and elutriation of particles from the bed starts. Channeling and slugging are not desired due to their adverse effects on bed operation. Gas leaves bed without any contribution to fluidization in the case of channeling. Slugging causes elutriation of particles and discontinuity in fluidization.

3.6 Minimum Fluidization Velocity for Binary Mixtures in Bubbling Fluidized Bed

Fluidized bed systems are utilized in a wide range of industrial operations which can require to process dissimilar materials that differ in their size, shape or density. Fluidization for binary or polydisperse systems is different than for that of monodisperse ones. Each component in the bed has its own fluidization characteristics and their mixture acts in different manner from the view of fluidization. Minimum fluidization velocity for binary or polydisperse systems should be well defined prior to design of a fluidized bed system. As Zhanyong Li [10] emphasized, obviously, different hydrodynamics may occur in a bed composed of dissimilar solids compared to the homogeneous bed of a single component. The minimum fluidization velocity is one of the important fundamental parameters to know at the beginning for design and operation of such fluidized beds. To estimate the minimum fluidization velocity for a binary system, it is necessary to take account of the different characteristics of the mixing and separation of two kinds of particles having different properties [11].

First part of the experimental works of this study aims to determine the minimum fluidization velocity for binary systems of biomass and silica sand mixtures. Definition of minimum fluidization velocity for binary systems is important since there is more than one definition in the literature.

The analysis of the fluidization properties of a binary mixture undergoing segregation by size presents, as a first difficulty, the problem of adopting a proper definition of its minimum fluidization velocity. As in the case of monodisperse beds, the parameter U_{mf} not only quantitatively indicates the amount of drag force, needed to attain solid suspension in the gas phase, but also constitutes a reference for the evaluation of the intensity of the fluidization regime at higher velocity levels. Owing to the fact that the onset of fluidization is always accompanied by that of segregation phenomena, the definition of minimum fluidization velocity of a binary mixture is not obvious and has to be discussed in the light of the specific characteristics of the system [12].

Generally, the measurement of minimum fluidization velocity is based on the diagram of pressure drop versus superficial gas velocity. The value is obtained at the intersection of the two extrapolated linear portions of the plot corresponding to the complete fluidized bed region and the packed bed region, respectively. On the other hand, some authors such as Uchida et al. (1983) defined the complete fluidization velocity as the true minimum fluidization velocity for the bed of mixtures, considering that the whole bed is capable of being fluidized beyond that velocity. In principle, the difference between complete and minimum fluidization velocity tends to diminish for a bed of well-mixed solids [10].

Some researchers proposed empirical correlations to define minimum fluidization velocity for binary systems. They are generally based on size, shape, density and mass fraction of each component.

Cheung et al. [13] proposed the following correlation to determine minimum fluidization velocity for binary mixtures.

$$u_{mf} = u_s \left(\frac{u_s}{u_b} \right) x_b{}^2 \qquad (1)$$

where u_s and u_b are the minimum fluidization velocities for the smaller and larger particles in single component fluidized beds and x_b is the mass fraction for larger particle in a binary mixture. This correlation does not take into account the particle size or density.

Correlation proposed by Chiba et al [14] includes the densities and sizes of the components together with their minimum fluidization velocities and mass fractions.

$$u_{mf} = u_f \frac{\bar{\rho}}{\rho_f} \left(\frac{\bar{d}}{d_f} \right)^2 \qquad \text{(For a completely mixed bed)} \qquad (2)$$

$$u_{mf} = \frac{u_f}{(1 - u_f / u_{pk}) x_f + u_f / u_{pk}} \qquad \text{(For a completely segregated bed)} \qquad (3)$$

where u_f and u_{pk} are the minimum fluidization velocities for fluid and packed bed components in single component fluidized beds and x_f is the mass fraction of fluid component. $\bar{\rho}$ and $\bar{d}$ are the mean particle density and diameter based on volume fraction. $\bar{\rho}$ takes into account the components' densities and volume fractions whereas $\bar{d}$ components' particle sizes and volume fractions.

Noda et al [11] proposed the following correlation.

$$\mathrm{Re}_{p,mf} = \frac{\bar{d}_p\, u_{mf}\, \rho_g}{\mu} \tag{4}$$

where $\mathrm{Re}_{p,mf}$ is the particle Reynolds number at minimum fluidization, $\bar{d}_p$ is the mean particle size in a binary system based on mass fractions, ρ_g is the density of gas stream and μ is the viscosity of the gas stream. Definition of the $\bar{d}_p$ includes the particle sizes, densities and mass fractions of each components

In 1987, Bilbao et al [15] proposed the following correlation.

$$u_{vf} = u_{pk} - (u_{pk} - u_f)X_f \tag{5}$$

where u_f and u_{pk} are the minimum fluidization velocities for fluid and packed bed components in single component fluidized beds. u_{pk} is dependent on the particle size of packed bed component. X_f is volume fraction of fluid component and depends on densities and mass fractions of fluid and packed bed components.

Rao at al [16] also studied minimum fluidization velocities of biomass/sand mixtures. They argued that no previous equation was adequate for determining u_{mf} of the mixtures. They therefore developed new correlation based on an average effective mixture density and an effective particle diameter, i.e.

$$u_{mf} = \frac{d_{peff}^{\ 2}(\rho_{eff} - \rho_g)g}{1650\mu_g} \tag{6}$$

ρ_{eff} is the effective density of mixture that based on densities and weights of the sand and biomass particles. d_{peff} is the effective particle diameter of mixture that based on mean diameter, density and weight of the sand and biomass particles.

Results obtained from experiments for minimum fluidization velocity for biomass-silica sand mixtures in this study is compared with the above mentioned correlations and their success to predict our results is assessed in the results and discussions part.

3.7 Mixing and Segregation of Binary Mixtures in Bubbling Fluidized Beds

Gas-solid fluidized beds offer suitable technologies for many industrial processes. These processes may include dissimilar materials that have different sizes and/or densities. Problem may arise here is the possibility of poor fluidization inside the bed due to differences in materials physical properties. To choose the optimum operating conditions, hydrodynamic behavior of the bed should be well understood. Mixing and segregation degree inside the bed is an important point considering the hydrodynamic behavior of the bed.

Particle distribution especially in vertical direction is caused by mixing and segregation mechanisms. Degree of mixing and segregation of particles is crucial depending on the process requirements. As an example, segregation of particles is highly desirable for separation processes or as Geldart [9] drew attention for a fluidized bed combustor, the rapid dispersion of injected combustible matter amongst the inert ash particles (the micro-mixing) affects crucially the combustion efficiency, whilst the overall solids circulation rate within the bed strongly influences the vertical and radial temperature profiles.

The fluidization of particles with more than one density or size gives rise to a steady distribution of mixture components along the bed height which depends both on constitutive particle properties and on the whole set of operative and geometric conditions of the process. From one extreme to another, the system may be formed by a unique well-mixed phase or by distinct layers of each of the solid species, but more frequently an intermediate component distribution is observed [12].

The driving mechanism for mixing in a fluidized bed is the formation of bubbles. Movement of a bubble starts at the distributor plate and as it moves upwards, coalescence with other bubbles results in increase in their size and velocity. They are assumed to have spherical shape in their idealized form. In their wake, bed material is carried along bed height and some other material is carried by the created drift mechanism. Particle in wake and drift are exchanged with bed material during traveling upwards. When it reaches to the surface, it bursts and dispels the particles in the ballistics directions. Dispelled particles move downwards near to the bed wall. Geldart [9] named particle exchange between bubble and its surrounding in the wake and drift as "micro mixing" and whole movement of material by movement of particles downwards to replace that carried upwards as "macro mixing". Macro together with micro-mixing creates a well mixed bed.

Chiba et al. [14] classified the mixing state in the fluidized bed of binary system into three cases, that is, (a) complete mixing, (b) complete segregation and (c) partial mixing. When a bed of binary system is fluidized, one component is generally fluidized at the lower gas velocity, and the other at the higher velocity. In general, if the density of one component is different from the other, the heavier component tends to sink while the lighter one rises. The former component is called jetsam and the latter flotsam [11].

Solids that have a wide particle-size distribution have been shown to exhibit segregation due to differences in drag per unit length [17]. Particles of equal density exhibiting a higher drag per unit weight tend to behave as flotsam, while those with lower drag are jetsam. Generally, this results in larger particles accumulating at the bottom of the bed. However, particles of different densities are more likely to segregate than in systems with a wide size distribution [18].

To evaluate the mixing quality of biomass-silica sand mixtures, mixing index (MI) should be introduced. It is defined as the ratio of local to overall concentration of biomass in sand media. MI = 1 is ideal mixing condition.

$$MI = \frac{x_{local}}{x_{overall}} \qquad (7)$$

Experimental results presented in section 5.2 shows the mixing pattern formed in the bed during fluidization of biomass-silica. y-axis of the figures given in that section presents mixing index (MI) for each layer.

CHAPTER 4

EXPERIMENTAL SET-UP, EQUIPMENT AND METHODOLOGY

Experimental works of this study consists of three parts. First part covers the determination of minimum fluidization velocity for mixtures of biomass-silica sand and the comparison of experimental results with the proposed correlations available in the literature. Second part aims to investigate mixing/segregation behaviors of mixtures of biomass-silica sand. Third part of the experimental works examines the fluidization and bubbling characteristics of mentioned mixtures in a 2-D fluidized bed.

4.1 Experimental Set-up and Methodology for Determining Minimum Fluidization Velocity of Binary Mixtures of Biomass-Silica Sand

Experiments to determine minimum fluidization velocity of biomass-silica sand mixtures were carried out in a column of cylindrical plexiglass bed with 14.6 cm internal diameter. The schematic of the experimental set-up is shown in Figure 4.1. The bed height was 2 meters to provide good observations for freeboard region. Top of the bed was covered with a mesh wire to prevent elutriation of the particles. The distributor plate is a perforated plate having 256 holes of 1.5 mm in diameter to provide uniform air distribution. 63 micron mesh wire was placed over the distributor plate to prevent fall of fine particles through holes. 15 cm long wind box that has the same diameter with bed was installed under the distributor plate acting as an air reservoir.

The fluidizing medium was air and it was supplied by a compressor. Pressure of the air exiting the compressor was adjusted by a pressure regulator and then it was passed through a rotameter to measure its flow rate. Air flow rate was adjusted by a valve inserted before the rotameter. To measure the pressure drop along the bed height a U-type water manometer was used. By reading air flow rate from rotameter and corresponding pressure drop from U-type water manometer, fluidization curves were drawn for each mixture. For all experiments bed height was kept 15 cm. Prior to the each experiment, mixture was fluidized for a long time and the gas flow suddenly cut to obtain well mixed bed before beginning of experiments. All experiments carried out three times and averages of them are used to draw fluidization curves. To present deviations in experimental results, error bars are placed into the fluidization curves.

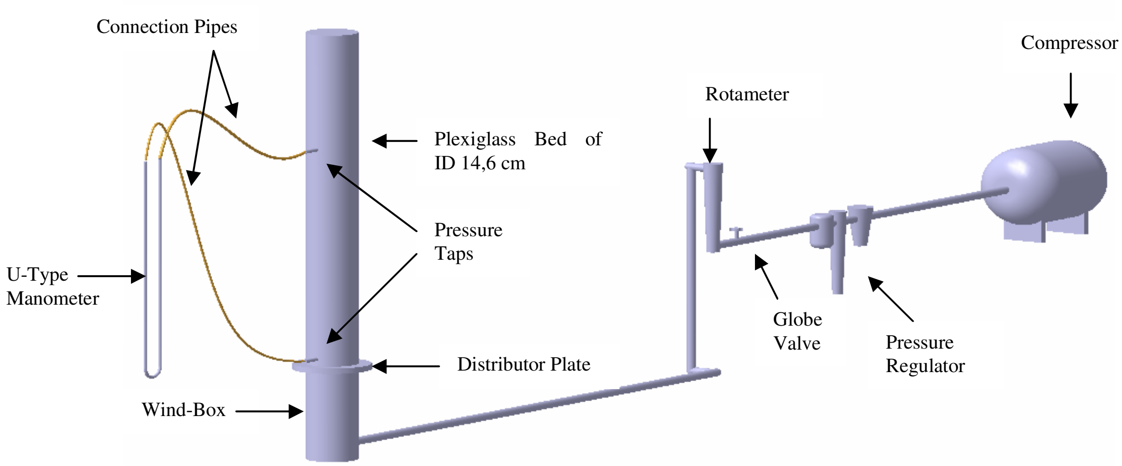


Figure 4.1 Experimental Set-up to Determine Minimum Fluidization Velocity of Biomass-Silica Sand Mixtures

Table 4.1 shows the experiments conducted in the content of this part. Five different biomass materials form mixture with three different types of silica sand each having different particle size. Silica sand with particle size 595-850 μm was utilized to form mixture only with olive cake and hazelnut shell. As a result of experiments conducted by silica sand with particle size 150-425 μm and 425-595 μm, it is found that mass fraction change of olive husk and hazelnut shell does not lead any change in minimum fluidization velocity of the mixture. For this reason experiments were carried out by employing mixtures constituted by mentioned biomass materials with silica sand with particle size of 595-850 μm to investigate widely the effect of silica sand particle size on minimum fluidization velocity of mixture.

Table 4.1 Experiments for Determining Minimum Fluidization Velocity of Biomass-Silica Sand Mixtures

Biomass Material	Mass Fraction of Biomass (%) in the Mixture	Silica Sand (150-425 μm)	Silica Sand (425-595 μm)	Silica Sand (595-850 μm)
Rice Husk	2	MF (1)	MF (4)	
	5	MF (2)	MF (5)	
	10	MF (3)	MF (6)	
Sawdust	2	MF (7)	MF (10)	
	5	MF (8)	MF (11)	
	10	MF (9)	MF (12)	
Wheat Straw	2	MF (13)	MF (16)	
	5	MF (14)	MF (17)	
	10	MF (15)	MF (18)	
Olive Cake	2	MF (19)	MF (22)	MF (25)
	5	MF (20)	MF (23)	MF (26)
	10	MF (21)	MF (24)	MF (27)
Hazelnut Shell	2	MF (28)	MF (31)	MF (34)
	5	MF (29)	MF (32)	MF (35)
	10	MF (30)	MF (33)	MF (36)

4.2 Experimental Set-up and Methodology for Determining Mixing and Segregation Behavior of Binary Mixtures of Biomass-Silica Sand

Mixing experiments were conducted again in a cylindrical Plexiglas bed of 14.6 cm internal diameter and 2 meters height. Top of the bed was covered with a mesh wire to prevent elutriation of the particles. Distributor plate, wind box compressor, pressure regulator and rotameter are all the same that used in minimum fluidization velocity experiments. To determine the mixing and segregation behavior of the mixtures of biomass and silica sand, freezing method was employed. This method was used by researchers Nienow et al., 1978; Wang and Chou, 1995; Wirsum and Fett, 1997; Wu and Baeyens, 1998 and they obtained the degree of solids mixing experimentally by the following steps: (a) freezing the bed by a sudden stop of the gas supply, (b) dividing the frozen bed into a number of sections, (c) removing the particles in these sections, and (d) analyzing the size or density distributions of the particles for each section [25].

In this study, openings were drilled at every 3 cm from distributor plate in the vertical direction and totally five layers were obtained as shown in Figure 4.2. Metal plates with circular shape were prepared for inserting to the openings to separate layers. Prior to each experiment, fluidizing air velocity was adjusted to provide $U_0 / U_{mf} = 2$ and then gas supply was cut by closing the valve. Silica sand and biomass materials were placed into the bed such as latter above the former. Total bed height was set to 15 cm for each experiment. Gas supply is started by sudden opening of the valve and after waiting long time enough for the bed to reach steady state operation. Gas supply was suddenly cut by closing the valve. After inserting the circular metal plates through the openings on the bed walls, material at each layer was extracted by a vacuum cleaner.

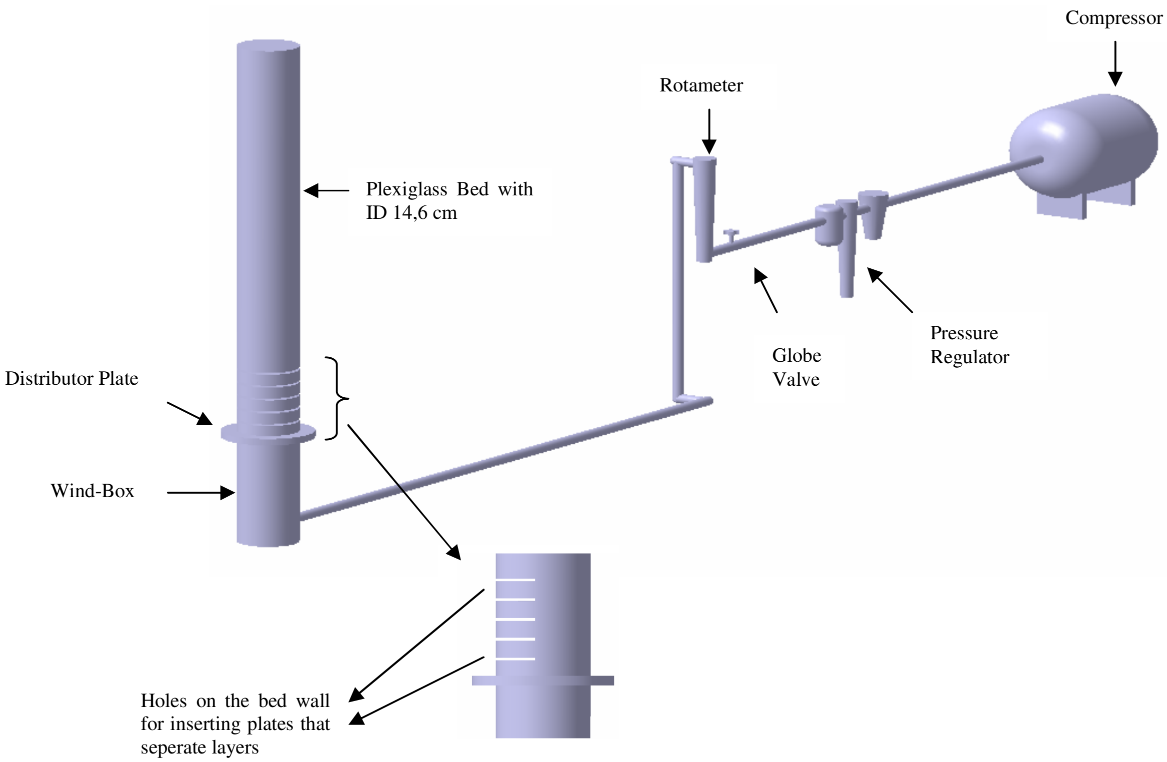


Figure 4.2 Experimental Set-up to Determine Mixing and Segregation Behavior of Biomass-Silica Sand Mixtures

After extracting material from each layer, biomass and silica sand particles were separated from each other. Weighing each compound, mass fraction of biomass material at each layer was determined. Three separation methods were used in the mixing experiments. Sieving was employed for silica sand-rice husk, wheat straw and hazelnut shell mixtures. Each of these mixtures was easily separated by sieving due to their different particle size. Although it was relatively unsuccessful, burning method was used for separation after eliminating big olive cake and sawdust particles by sieving to determine olive husk and sawdust mass fraction at each layer.

Table 4.2 shows the experiments carried out for determination of mixing/segregation behavior of biomass-silica sand mixtures. Experiments for sawdust-silica sand and olive cake-silica sand were only carried out for mixture having 5% biomass by weight and silica sand with particle size 150-425 μm due to separation difficulties.

Table 4.2 Experiments for Determining Mixing and Segregation Behavior of Biomass-Silica Sand Mixtures

Biomass Material	Mass Fraction of Biomass (%) in the Mixture	Silica Sand (150-425 μm)	Silica Sand (425-595 μm)
Rice Husk	2	MX (1)	MX (4)
	5	MX (2)	MX (5)
	10	MX (3)	MX (6)
Sawdust	2		
	5	MX (7)	
	10		
Wheat Straw	2	MX (8)	MX (11)
	5	MX (9)	MX (12)
	10	MX (10)	MX (13)
Olive Cake	2		
	5	MX (14)	
	10		
Hazelnut Shell	2	MX (15)	
	5	MX (16)	MX (18)
	10	MX (17)	

4.3 Experimental Set-up and Methodology for Determining Fluidization and Bubbling Characteristics of Binary Mixtures of Biomass-Silica Sand

A two dimensional fluidized bed was used to conduct experiments for observing fluidization and bubbling behavior of biomass-silica sand mixtures as shown in Figure 4.3. Bed is made of plexiglass to provide transparency that will allow taking images of the bed easily. The bed has dimensions of 15 mm width, 490 mm length and 1200 mm height. Fluidizing air was again supplied by the compressor, pressure of it was regulated by pressure regulator and flow rate was measured by a rotameter. Back side of the bed was illuminated to detect the bubbles and a video camera was used to capture images.

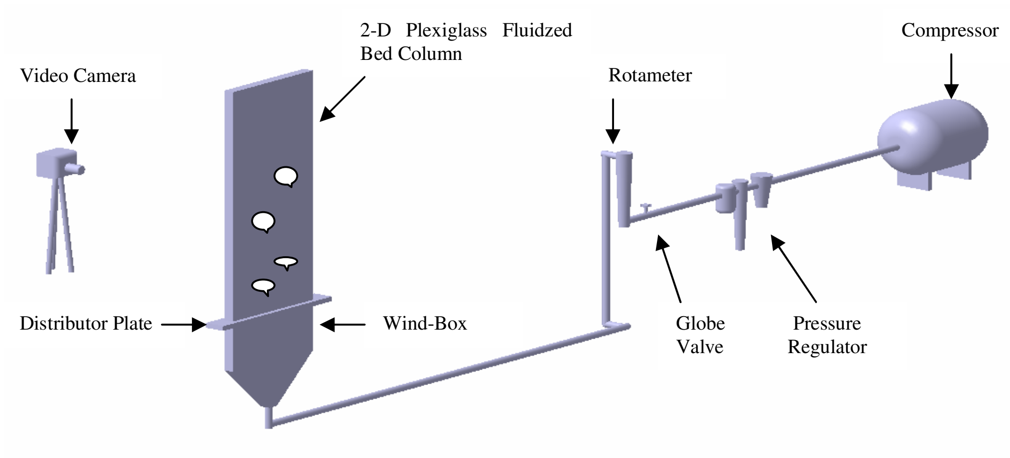


Figure 4.3 Experimental Set-up to Investigate Bubbling Characteristics of Biomass-Silica Sand Mixtures

Table 4.3 shows the experiments carried out for this part. Mixtures with 2%, 5% and 10% of biomass mass fractions were used as bed material. Height of the bed material was kept 25 cm. U_0 / U_{mf} ratio was adjusted as 1.5, 2.0 and 2.5 for each mixture and images taken at these velocities were assessed to decide whether the fluidization behavior of the bed material has desired characteristics or not. Prior to the experiments conducted with mixtures of biomass and silica sand, pure biomass and pure silica sand were fluidized in the 2-D column to guide comments for fluidization of mixtures.

Table 4.3 Experiments for Investigating Fluidization Characteristics of Biomass-Silica Sand Mixtures

Biomass Material	Mass Fraction of Biomass (%) in the Mixture	U/Umf = 1.5	U/Umf = 2.0	U/Umf = 2.5
Rice Husk	2	FC (1)	FC (4)	FC (7)
	5	FC (2)	FC (5)	FC (8)
	10	FC (3)	FC (6)	FC (9)
Sawdust	2	FC (10)	FC (13)	FC (16)
	5	FC (11)	FC (14)	FC (17)
	10	FC (12)	FC (15)	FC (18)
Wheat Straw	2	FC (19)	FC (22)	FC (25)
	5	FC (20)	FC (23)	FC (26)
	10	FC (21)	FC (24)	FC (27)
Olive Cake	2	FC (28)	FC (31)	FC (34)
	5	FC (29)	FC (32)	FC (35)
	10	FC (30)	FC (33)	FC (36)
Hazelnut Shell	2	FC (37)	FC (40)	FC (43)
	5	FC (38)	FC (41)	FC (44)
	10	FC (39)	FC (42)	FC (45)

4.4 Materials

Binary mixtures used this study is formed by a biomass and a silica sand. Five different biomass materials and silica sand with three different particle sizes were employed as experimental materials.

4.4.1 Silica Sand

Silica sand is widely utilized in fluidized beds as an inert material. It is used to improve fluidization and it acts like heat transfer medium. In this study, silica sand was employed as an inert material to form mixtures with biomass materials. It was obtained from a casting factory. It is in the Group-B in Geldart's Classification of particles. It was sieved and three different particle sizes, 150-425 μm, 425-595 μm and 595-850 μm, were obtained to be used in the experiments. This classification aimed to investigate the effects of sand particle size on the fluidization and mixing of mixtures of silica sand and biomass materials. Silica sand having mentioned three different particles sizes have bulk density of about 1580 kg/m^3.

4.4.2 Biomass Materials

Five different biomass materials were used to determine their fluidization and mixing behaviors. They are all important biomass materials in Turkey. Some of physical and chemical properties of these biomass materials are given in Table 4.4.

Table 4.4 Physical and Chemical Properties of Biomass Materials

Values for Biomass Materials Used in this Study (*)

	Wheat Straw [27]	Olive Husk [27]	Hazelnut Shell [27]	Rice Husk [28]	Sawdust [29]
Moisture (%)	8,50	9,20	9,00	9.08 - 10.44	3,80
Proximate analysis (wt%d.b.)					
Volatile matter	63.00	70.30	69.30	63.00 – 70.20	81.50
Ash	13.50	3.60	1.40	15.30 – 24.60	2.40
Fixed carbon	23.50	26.10	28.30	10.20 – 14.50	12.30
Ultimate analysis (wt%d.b.)					
Carbon	45.50	50.00	52.90	37.60 - 44.50	48.20
Nitrogen	1.80	1.60	1.40	0.38 - 0.50	0.10
Hydrogen	5.10	6.20	5.60	4.70 - 5.51	5.80
Oxygen	34.10	42.20	42.70	31.50 - 35.20	39.80
HHV (MJ/kg)	17.00	19.00	19.30	14.72 - 18.31	20.40
Bulk Density (kg/m^3)	100.00*	527.00*	477.00*	97.00*	211.00*
Particle Density (kg/m^3)	905.00*	1385.00*	1103.00*	980.00*	947.00*

4.4.2.1 Rice Husk

Rice husk is an agricultural residue that remains as a result of rice production in rice factories. Annual rice husk production in Turkey is 0.4 million tons and its energy potential is 0.1 million of equivalent oil [29]. It is mainly produced in Aegean, Black-sea and Marmara regions of the country. It is generally burned in conventional burners to supply heat. It is also used in poultry farming to be laid under chickens or it is eliminated by burning without any energy production. Its utilization as an energy source contributes to the sustainability of the Turkey's energy in an environmental friendly manner. Rice husk used in this study was obtained from Beypazarı Rice Factory and particles have average dimensions of 7.7x2.7x1.3 mm.

4.4.2.2 Wheat Straw

Wheat straw is a lignocellulosic agricultural residue that can be gasified with air in order to obtain a low BTU fuel gas which can be used in steam or electrical energy generation [15]. Wheat straw is the most abundant agricultural residue in Turkey. Its annual production was 26.4 million tons and corresponding energy value was 7.2 million of oil equivalent in 2001 [29]. It is mostly used to feed animals. After harvesting wheat from plantation, wheat and its straw separated from each other straw is cut into smaller lengths by pathosis. Wheat straw obtained from a plantation for this study was approximately 4-5 cm in length and since this would create problems for fluidization in the 14.6 cm ID fluidized bed, they were cut into smaller pieces by using a chopper to provide good fluidization characteristics with silica sand. After chopping their lengths were in the range of 4-12 mm and the particles have average dimensions of 7x1x0.3 mm.

4.4.2.3 Sawdust

Sawdust is residue that forms in the saw milling industry. It consists of fine wood particles. It serves as an important renewable energy source especially for the countries that have developed forestry industry. In the year 2005, in Finland, the wood-based fuels covered about 20% of the energy consumption and, after oil products, where the second most important source of energy [30]. Sawdust used in this study is obtained from a wood processing plant. Its particle size distribution is given in the Figure 3.4.

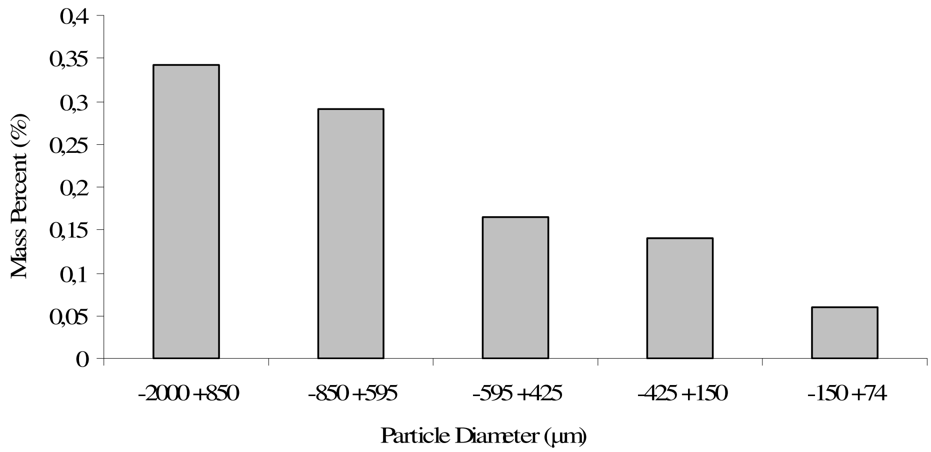


Figure 4.4 Particle Size Distribution of Sawdust

4.4.2.4 Olive Cake

With the energy picture getting worse everyday, it is now desirable to search for alternative energy sources. This lead to renewed interest in olive cake as an alternative energy source in Turkey due to some of its advantages, such as negligible sulfur content, reducing environmental impact, low cost compared to fossil fuels, problem free storage and lack of transportation requirements if used in an olive oil production facility. Olive cake is a byproduct of oil production and is a solid material consisting of seed particles and the fleshy parts of olives. Turkey is among the top 5 main olive oil-producing countries in the world [31]. Turkey produces 8.41% of the total olive in the world. This production corresponds to 1,250,000 tons per year (average of productions between 1994-2004). As a rough estimate, the total recoverable energy potential of olive cake is considered as 5 PJ which is equivalent to 199.4 Ktoe [32]. It is available mostly in Mediterranean countries due to their high olive cultivation levels. Its utilization as an energy source not only provides energy but also eliminates the disposing problem of it. Particle size distribution of olive cake used in this study is given in Figure 4.5. Particle size range varies largely. It has very fine particles with particle size smaller than 425 μm whereas it also has particles bigger than 2 mm.

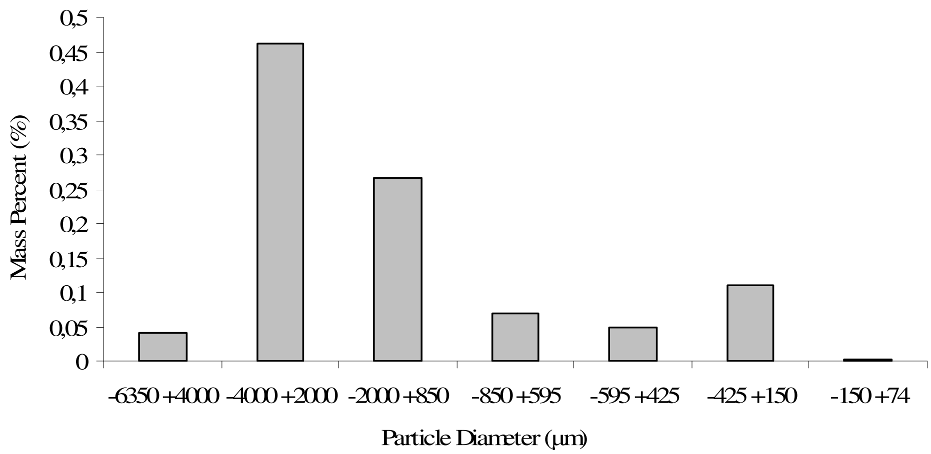


Figure 4.5 Particle Size Distribution of Olive Cake

4.4.2.5 Hazelnut Shell

Turkey is the biggest producer of hazelnut in the World. It is mainly cultivated in the black-sea region. Its shell is stands as an important agricultural residue. Its annual production was 0.8 million tons and corresponding energy value was 0.3 million of oil equivalent in 2001 [29]. It is mainly used as fuel and conventional burners are employed to supply heat from hazelnut shell. Hazelnut shell used in this study is crunched after separated from edible part. Crunched particles were sieved and particles accumulated between mesh openings 4 and 2 mm were employed in the experiments.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Minimum Fluidization Velocity for Binary Mixtures of Biomass and Silica Sand

This section presents the results of the experiments carried out for determining the minimum fluidization velocities of binary mixtures of biomass-silica sand.

5.1.1 Fluidization Curves of Silica Sand with Three Different Particle Sizes

Determination of minimum fluidization velocities of silica sands guides the fluidization behaviors of biomass-silica sand mixtures. Silica sand used in this study has three different particle sizes, namely 150-425 μm, 425-595 μm and 595-850 μm. Their fluidization curves are given in Figures 5.1-5.3. Increase in particle size of silica sand causes increase in minimum fluidization velocity.

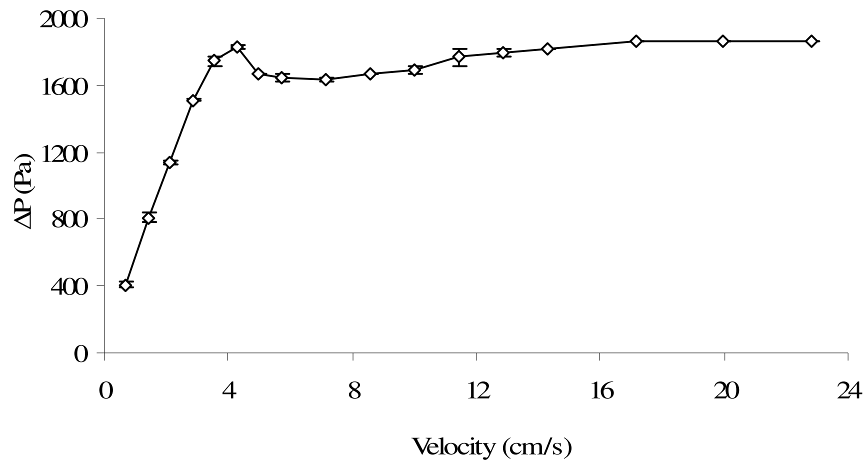


Figure 5.1 Fluidization of Silica Sand with Particle Size 150-425 µm

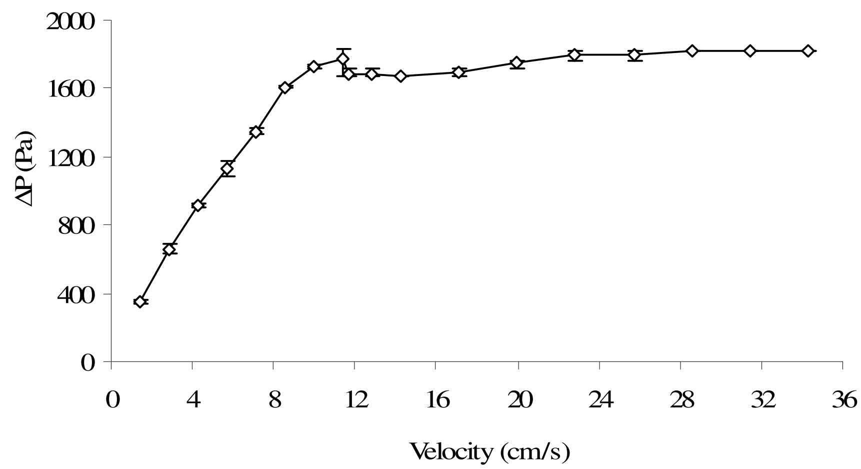


Figure 5.2 Fluidization of Silica Sand with Particle Size 425-595 µm

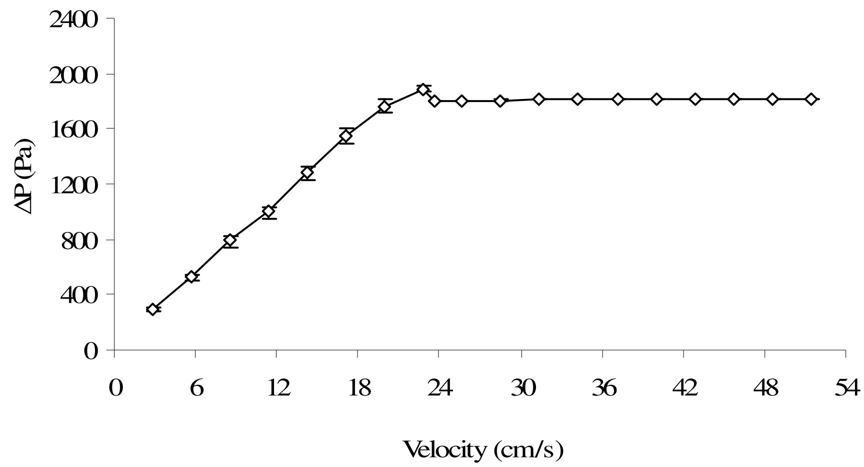


Figure 5.3 Fluidization of Silica Sand with Particle Size 595-850 μm

5.1.2 Rice Husk-Silica Sand Mixtures

Rice husk a major by-product of the rice milling industry, is one of the most commonly available lignocellulosic materials that can be converted to different types of fuels or chemical feedstocks through a variety of thermochemical conversion processes [28]. Its gasification and combustion in a fluidized bed are preferable processes to produce heat, combustible gases or electricity. Better design and problem-free operation of a fluidized bed requires clear understanding of bed hydrodynamics due to its direct relation to the process inside the bed.

Fluidization of rice husk is difficult due to its inappropriate physical properties such as shape and density. Fluidization and defluidization curves of rice husk are given in Figure 5.4. As the velocity of the fluidizing gas increases, pressure drop along the bed also increases up to some point where the pressure fluctuations start. Channel formation and movement of these channels to the different locations inside the bed are the main reasons of these pressure fluctuations. Deviations in pressure readings for each experiment are large in mentioned velocity range and this results in large error bars. At the superficial gas velocity of 1 m/s, fluctuations ceases and rice husk fluidizes as can be inferred from the figure that pressure stays constant after that point. Visual observations also support this situation. Turbulent-like flow pattern is formed instead of bubbling bed.

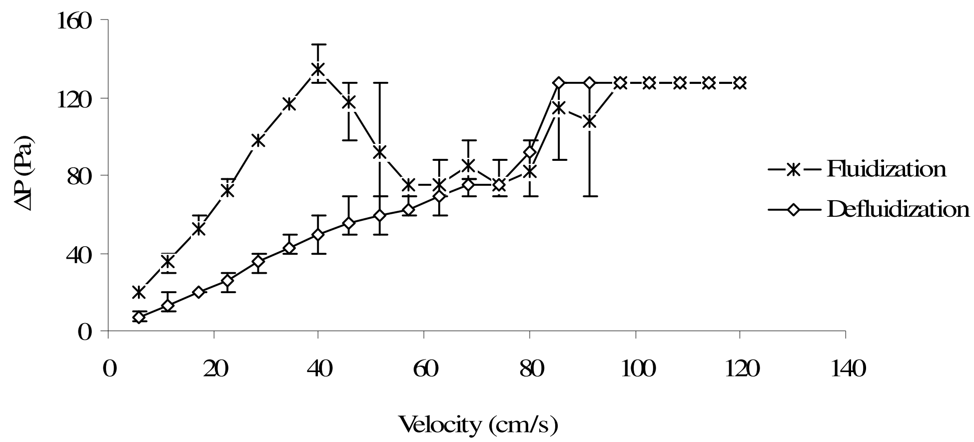


Figure 5.4 Fluidization and Defluidization of Rice Husk

Major problem with the fluidization of rice husk is the necessity of high gas velocities. Mixing of rice husk with an inert material is an extensively utilized method in industrial operations and can reduce the minimum fluidization velocity noticeably. Mentioned inert materials can be silica sand, limestone or any other appropriate material concerning the process inside the bed and fluidization behavior.

In this study, silica sand with two different particle sizes is used to form mixtures with rice husk. Experiments were conducted to observe the effects of rice husk mass fraction and the silica sand particle size on minimum fluidization velocity of the mixture. Mixtures with 2% rice husk on mass basis fluidize well as shown in Figure 5.5. Channeling problems occurs before fluidization for the mixtures of 5% and 10% mass fractions but minimum fluidization velocity is still less than that of pure rice husk. Figure 5.6 shows the experiments carried out with silica sand that have particle size 425-595 μm. If Figure 5.5 and Figure 5.6 are compared, it will be observed that fluidization curves are similar to each other for the same rice husk mass fractions. The only difference is the change in minimum fluidization velocity.

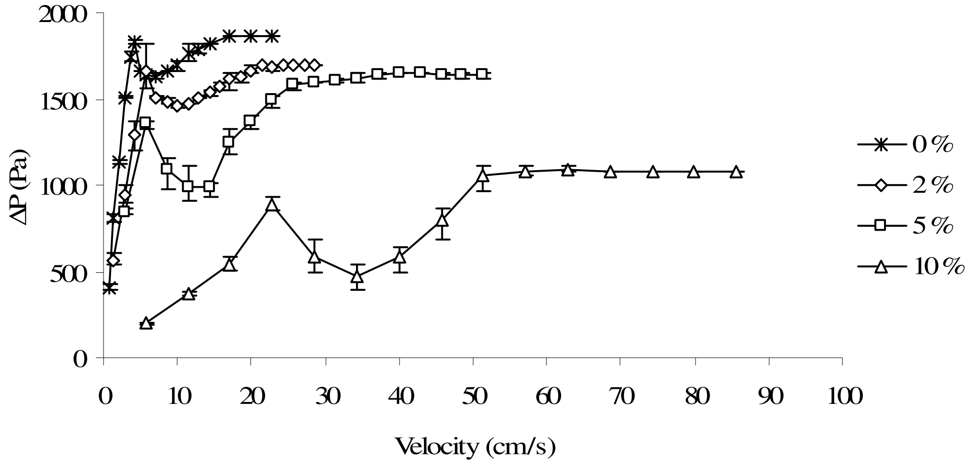


Figure 5.5 Fluidization of Rice Husk-Silica Sand (150-425 μm) Mixtures with 2%, 5% and 10% Mass Percent of Rice Husk

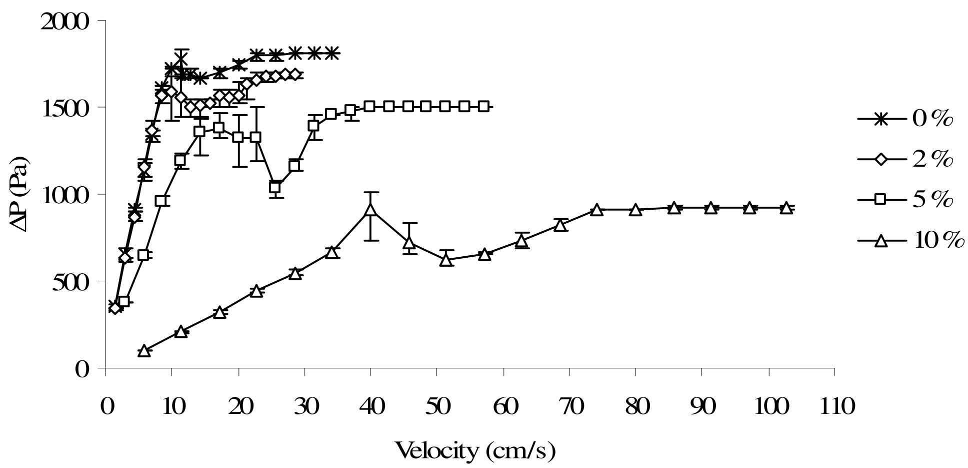


Figure 5.6 Fluidization of Rice Husk-Silica Sand (425-595 μm) Mixtures with 2%, 5% and 10% Mass Percent of Rice Husk

Effects of rice husk mass fraction and the silica sand particle size on minimum fluidization velocity can be clearly seen from the Figure 5.7. Increase in mass fraction dramatically increases the minimum fluidization velocity of the mixture for both sizes of silica sand. Silica sand particle size also affects the minimum fluidization velocity but mass fraction of rice husk seems to have dominant effect. Since the density of rice husk is too small compared with the density of silica sand, changes in mass fraction of rice husk results in larger changes in volume fractions and this is the main reason of increase in minimum fluidization velocities of the mixtures. Bubbling fluidization was achieved for all types of mixtures.

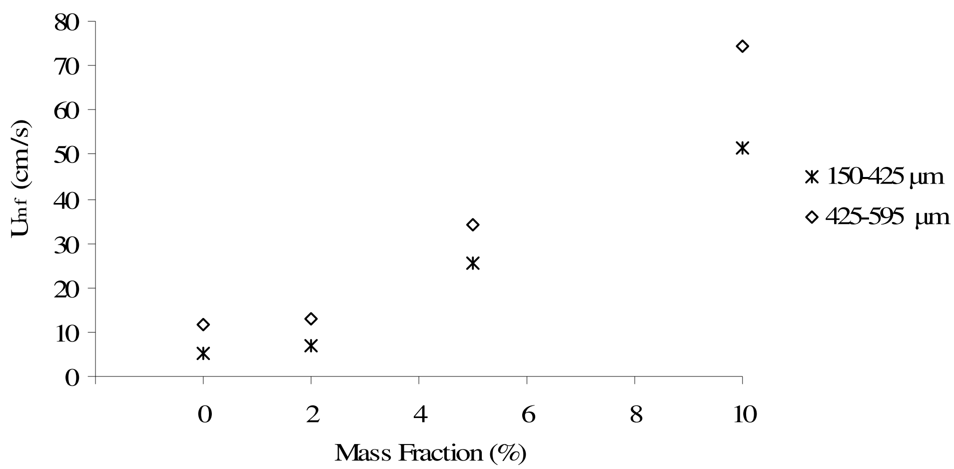


Figure 5.7 Effect of Mass Fraction of Rice Husk in the Mixture on the Minimum Fluidization Velocity

5.1.3 Sawdust-Silica Sand Mixtures

Biomass such as sawdust can be processed by gasification or pyrolysis in gas-solid fluidized beds yielding fuel gases (Aznar et al., 1992). By itself, sawdust does not fluidize well and exhibits channeling and Geldart C fluidization behavior (Aznar et al., 1992a and Reina et al., 2000). Reina et al., (2000) theorize that aggregation of the sawdust occurs due to interlacing between unattached fibers, forming nets that retain other finer particles. One means of enhancing sawdust fluidization is by adding a second, inert component to the fluidized bed, such as sand (Aznar et al., 1992a).

In the present study, silica sand is utilized to enhance the fluidization of the sawdust by composing binary mixtures. Effects of sawdust mass fractions in the mixture and silica sand particle size on minimum fluidization velocity were investigated. Figure 5.8 shows fluidization and defluidization curves of pure sawdust. If fluidization curve is examined, decrease in pressure drop before fluidization can clearly be seen. This change is caused by channel formation in the bed. Deviations in pressure readings for each experiment are large within velocity range where channel formation is observed in the bed and this results in large error bars.

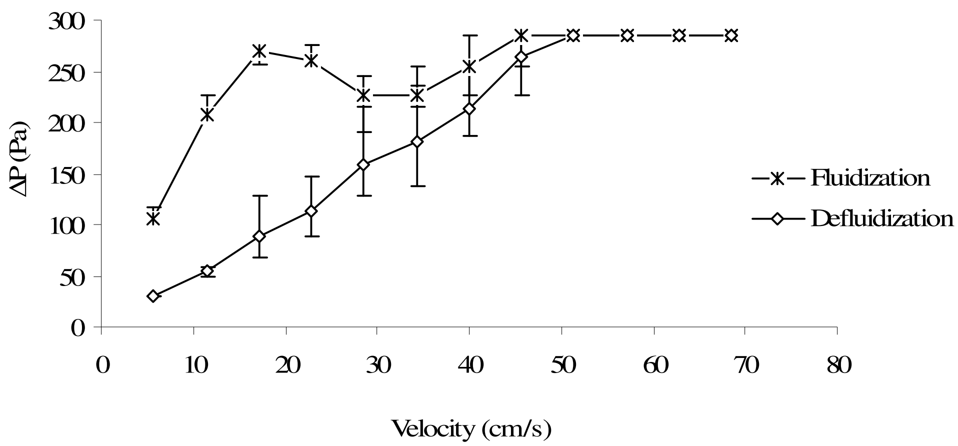


Figure 5.8 Fluidization and Defluidization of Sawdust

Figure 5.9 and 5.10 shows the fluidization curves of sawdust-silica sand mixtures. As can be inferred from the figures minimum fluidization velocities for mixtures are much less than minimum fluidization velocity of pure sawdust. Silica sand improves fluidization characteristics of sawdust significantly.

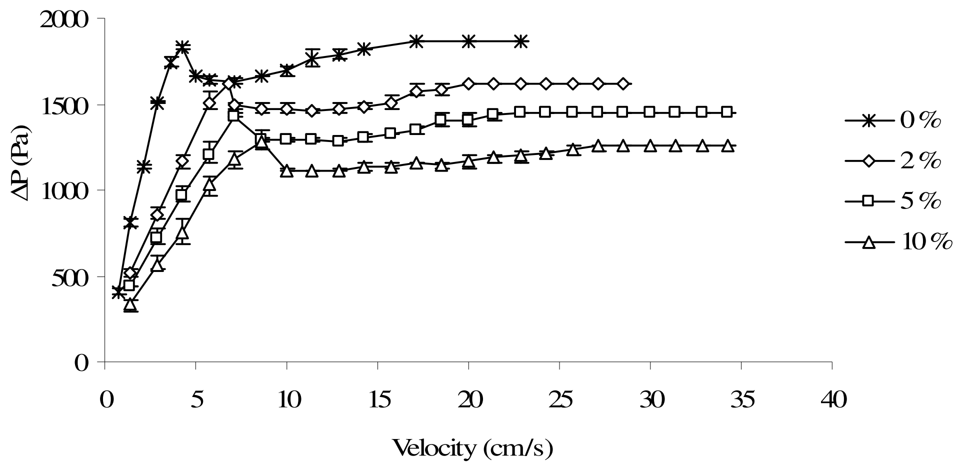


Figure 5.9 Fluidization of Sawdust-Silica Sand (150-425 μm) Mixtures with 2%, 5% and 10% Mass Percent of Sawdust

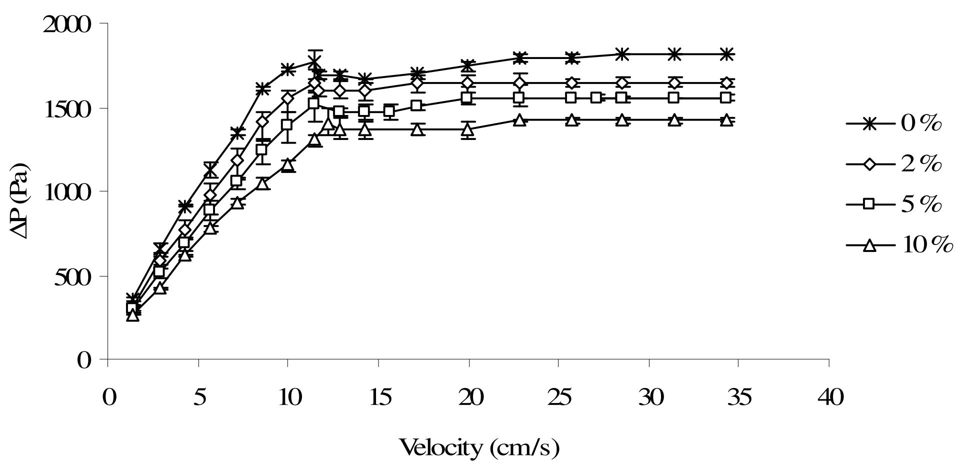


Figure 5.10 Fluidization of Sawdust-Silica Sand (425-595 μm) Mixtures with 2%, 5% and 10% Mass Percent of Sawdust

Figure 5.11 shows the effects of sawdust mass fraction and silica sand particle size on minimum fluidization velocities of mixtures. Mass fraction increase of sawdust lead to the increase in minimum fluidization velocity for mixtures formed by silica sand with 150-425 μm particle size. For the mixtures formed with silica sand with

425-595 μm particle size, mass fraction increase does not affect the minimum fluidization velocity of the mixture noticeably. Increase in sand particle size raises the minimum fluidization velocity. Mixing sawdust with silica sand resulted in considerable decrease in minimum fluidization velocity as compared to the sawdust's minimum fluidization velocity. Very well bubbling fluidization were achieved for all types of mixtures. Mixing of particles was also good due to well fluidized bed.

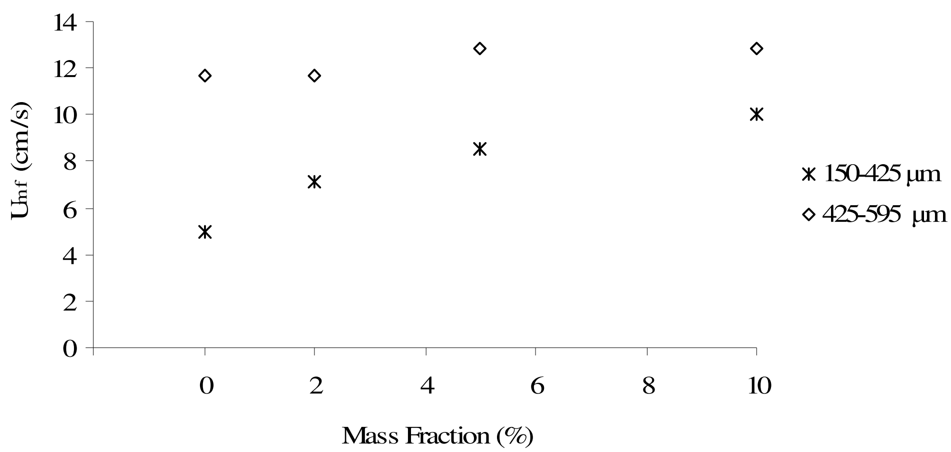


Figure 5.11 Effect of Mass Fraction of Sawdust in the Mixture on the Minimum Fluidization Velocity

5.1.4 Wheat Straw-Silica Sand Mixtures:

Wheat straw is the most abundant agricultural residue in Turkey. Fluidization characteristics of wheat straw can lighten the design of a fluidized bed gasifier or combustor. Pure wheat straw can not be fluidized due to its inappropriate physical properties. During fluidization, pressure drop along bed height increased linearly similar to a typical fluidization curves but beyond a velocity value of about 50 cm/s channel formation is observed in the bed and as the velocity is increased further, all bed material goes in the upward direction and it shows piston-like behavior. Fluidization was not possible as can be inferred from fluidization curve that is given by the Figure 5.12. Pressure fluctuations reveal channels and piston-like behavior of wheat straw.

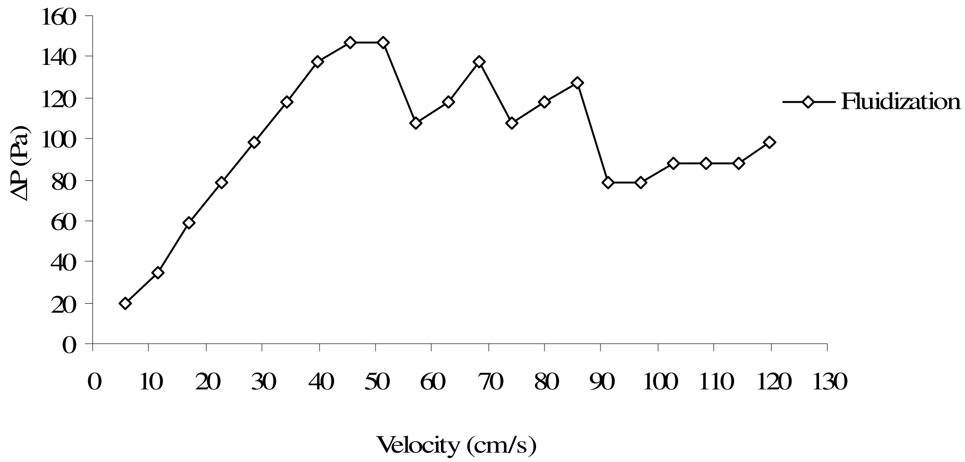


Figure 5.12 Fluidization of Wheat Straw

Mixture of wheat straw with silica sand can enhance the fluidization quality of the wheat straw. Figure 5.13 and 5.14 shows the fluidization curves of binary mixtures of wheat straw-silica sand. For mixtures having 2% and 5% mass fraction of wheat straw fluidize easily and their fluidization curves resembles typical fluidization curves. Channel formations were observed before fluidization for the mixtures having 10% wheat straw. This reflects to fluidization curves as nonlinear increase of pressure drop up to beginning of fluidization.

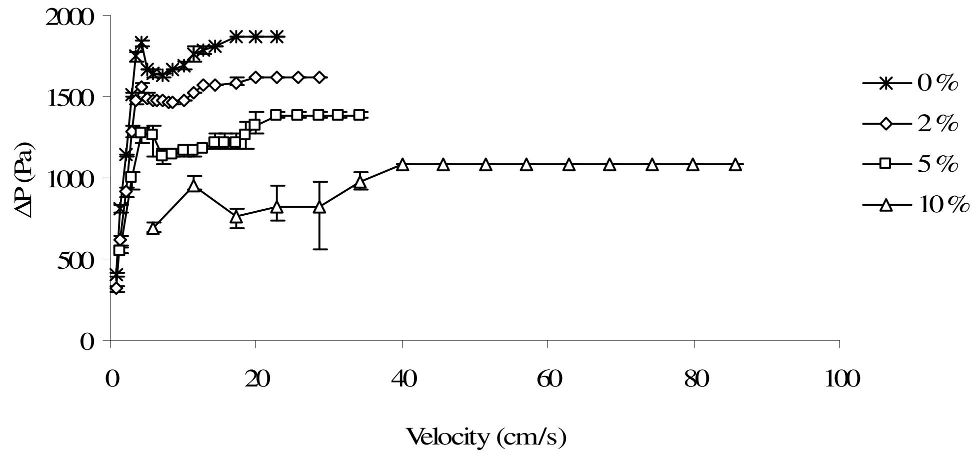


Figure 5.13 Fluidization of Wheat Straw-Silica Sand (150-425 μm) Mixtures with 2%, 5% and 10% Mass Percent of Wheat Straw

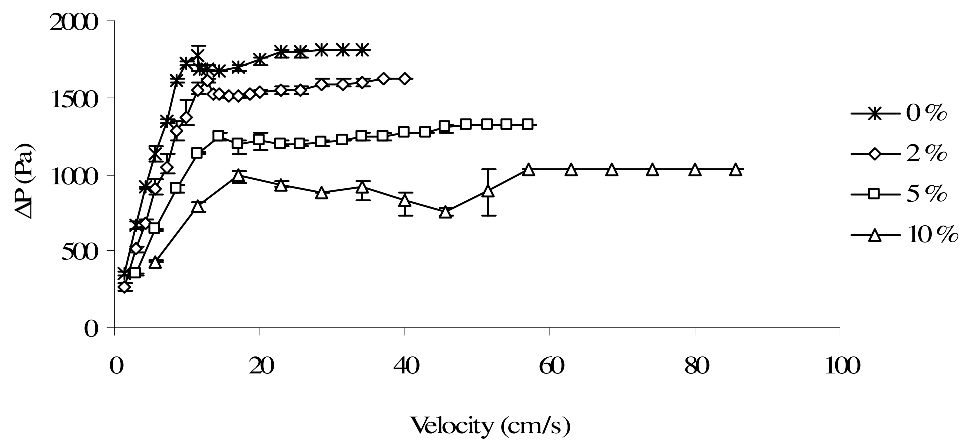


Figure 5.14 Fluidization of Wheat Straw-Silica Sand (425-595 μm) Mixtures with 2%, 5% and 10% Mass Percent of Wheat Straw

Mass fraction of wheat straw and sand particle size have noticeable effects on minimum fluidization velocity as seen from the Figure 5.15. Effect of wheat straw mass fraction is more dominant than silica sand particle size. Mass fraction increase of wheat straw causes exponential increase in minimum fluidization velocity of the mixture. This is an important data that should be taken into consideration for the design of fluidized bed combustor or gasifier.

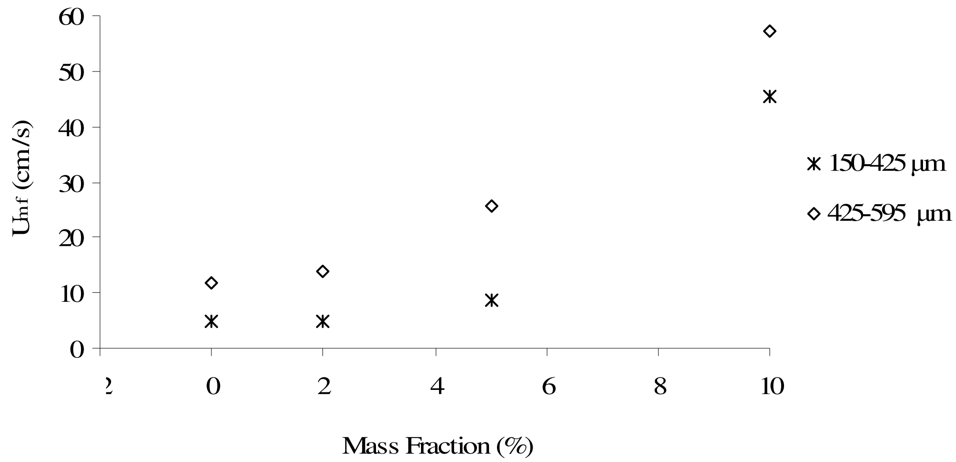


Figure 5.15 Effect of Mass Fraction of Wheat Straw in the Mixture on the Minimum Fluidization Velocity

5.1.5 Olive Cake-Silica Sand Mixtures:

Thermochemical processing of olive cake in a fluidized bed can be a preferable technology due to advantages of the fluidized beds. Hydrodynamic behavior of the bed is again a critical factor for the design and operation. Fluidization and defluidization curves for olive cake are given in the Figure 5.16. Olive cake is composed of particles varies in size largely as shown in Section 3.4.2.4 and during its fluidization, small particles fluidize firstly at lower gas velocities and whole bed fluidize after the superficial gas velocity exceeds the minimum fluidization velocity of the large particles.

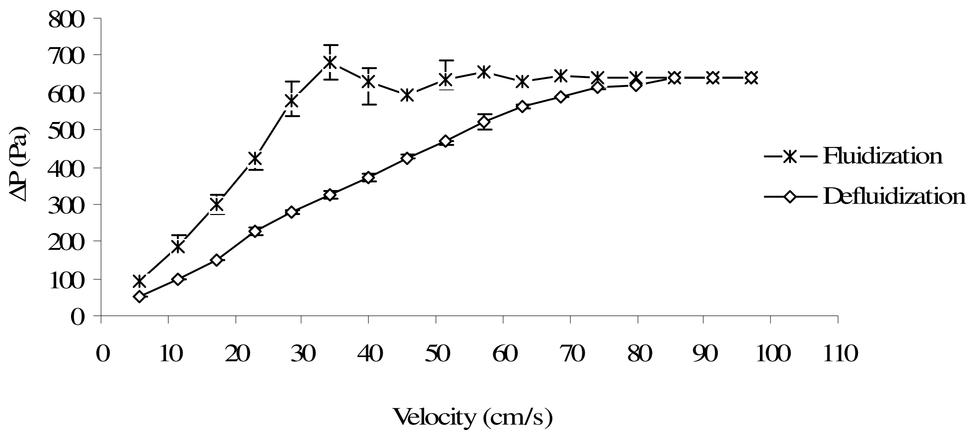


Figure 5.16 Fluidization and Defluidization of Olive Cake

Composing mixture of olive cake and silica sand provide better fluidization at smaller superficial gas velocities. Minimum fluidization velocities of the mixtures are very close to the minimum fluidization velocity of silica sand. Experimental results for mixtures formed by silica sand having three different particle sizes are given in the Figures 5.17-5.19. At each figure fluidization curves are very similar for each mass fraction of olive cake. There is a small difference only in their bed pressure drop value after fluidization attained. As the mass percent of olive increases, bed pressure drop value also decreases for fluidization state. This is due to the total mass decrease of mixture as olive cake mass fraction increases.

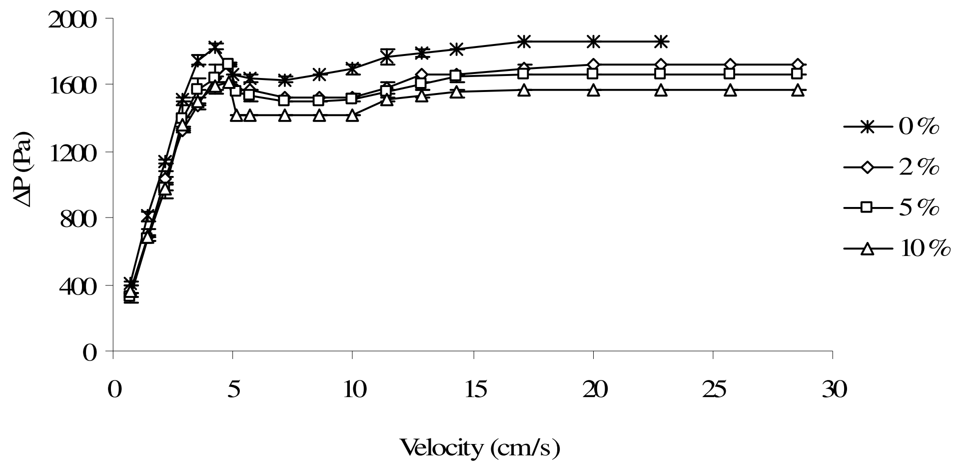


Figure 5.17 Fluidization of Olive Cake-Silica Sand (150-425 μm) Mixtures with 2%, 5% and 10% Mass Percent of Olive Cake

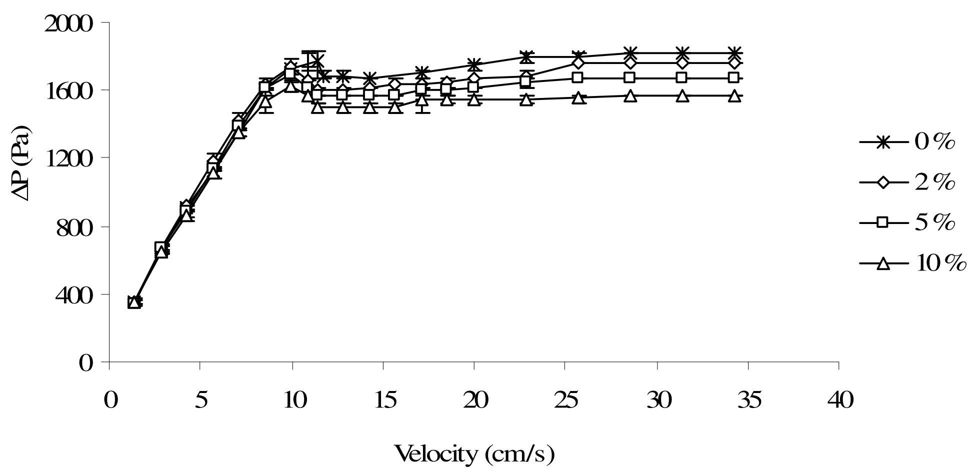


Figure 5.18 Fluidization of Olive Cake-Silica Sand (425-595 μm) Mixtures with 2%, 5% and 10% Mass Percent of Olive Cake

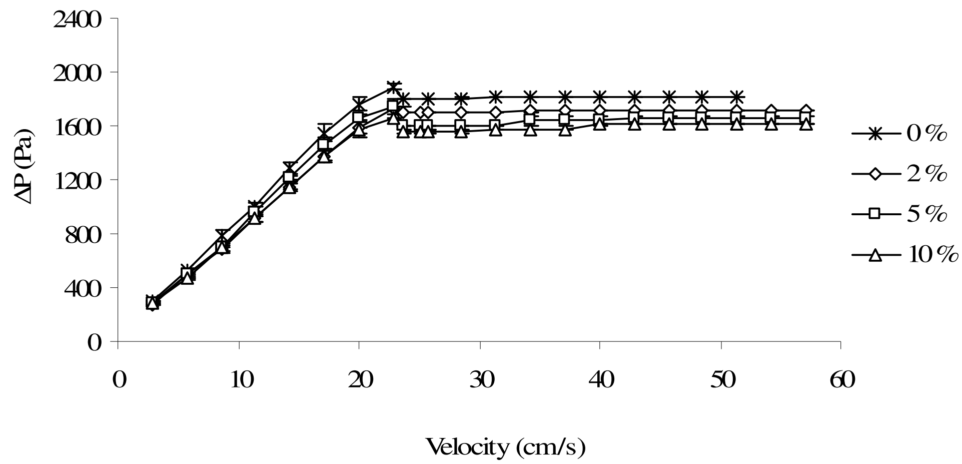


Figure 5.19 Fluidization of Olive Cake-Silica Sand (595-850 μm) Mixtures with 2%, 5% and 10% Mass Percent of Olive Cake

The noteworthy point here is that, minimum fluidization velocity of the mixture does not change if the mass fraction of the olive cake in the mixture increases as shown in Figure 5.20. It is due to the density, size and shape of the olive cake. Density of the olive cake is relatively much higher than the rice husk, sawdust and wheat straw and the shape of the olive cake particles are more spherical which results in better fluidization quality.

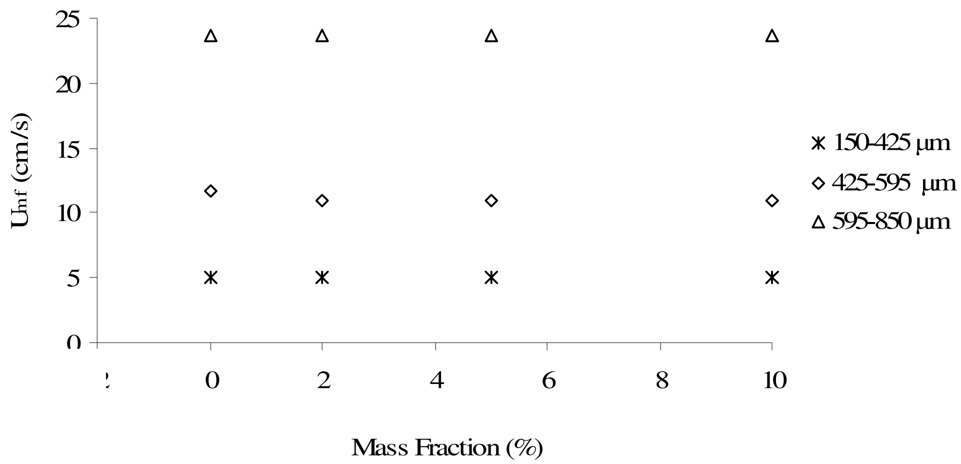


Figure 5.20 Effect of Mass Fraction of Olive Cake in the Mixture on the Minimum Fluidization Velocity

5.1.6 Hazelnut Shell-Silica Sand Mixtures

Turkey is the biggest producer of hazelnut in the world. In most of the production fields, hazelnut shell is burnt in conventional burners to supply heat. Fluidized bed is an appropriate technology to process hazelnut shell to produce heat or producer gas. Fluidization of hazelnut shell is very difficult since the non-spherical shape of the shell does not allow easy fluidization. Its fluidization can be possible at relatively high gas velocities depending on the size of the shell. Experiments for the mixtures of hazelnut shell and silica sand were conducted in this study to improve fluidization of hazelnut shell. Figure 5.21-5.23 shows the fluidization curves of mixtures constituted by silica sand having three different size and hazelnut shell. Each figure shows the fluidization curves of mixtures with three different mass fraction of hazelnut shell. For each mixture, the minimum fluidization velocity of the mixture is very close to minimum fluidization velocity of silica sand that it contains. At each figure, fluidization curves are very similar for each mass fraction of hazelnut shell. There is a small difference only in their bed pressure drop value after fluidization attained. As the mass percent of hazelnut shell increases, bed pressure drop value also decreases for fluidization state. This is due to the total mass decrease of mixture as hazelnut shell mass fraction increases.

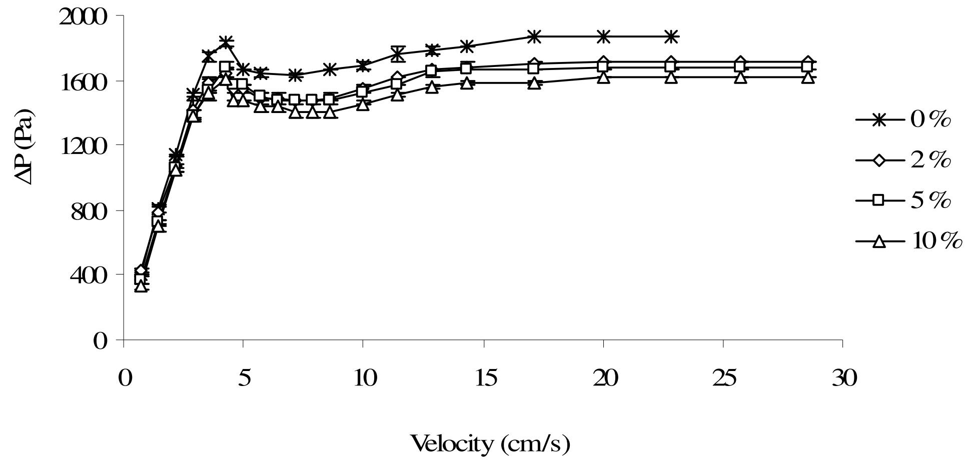


Figure 5.21 Fluidization of Hazelnut Shell-Silica Sand (150-425 μm) Mixtures with 2%, 5% and 10% Mass Percent of Hazelnut Shell

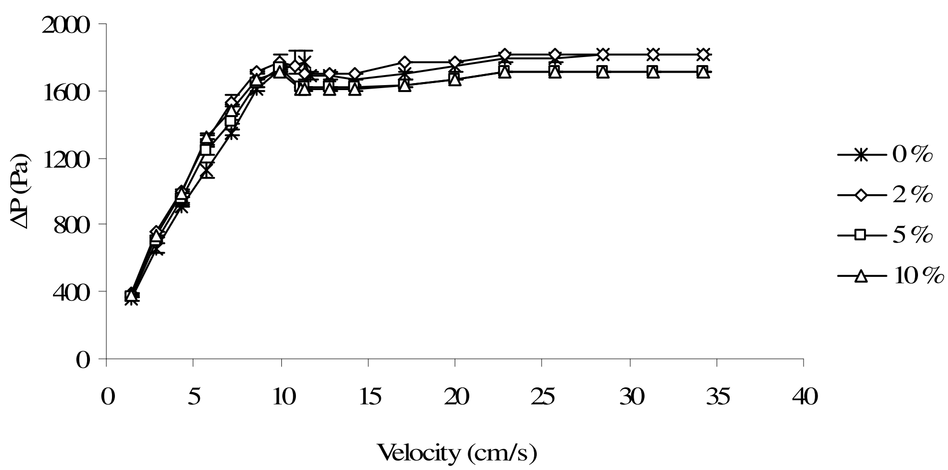


Figure 5.22 Fluidization of Hazelnut Shell-Silica Sand (425-595μm) Mixtures with 2%, 5% and 10% Mass Percent of Hazelnut Shell

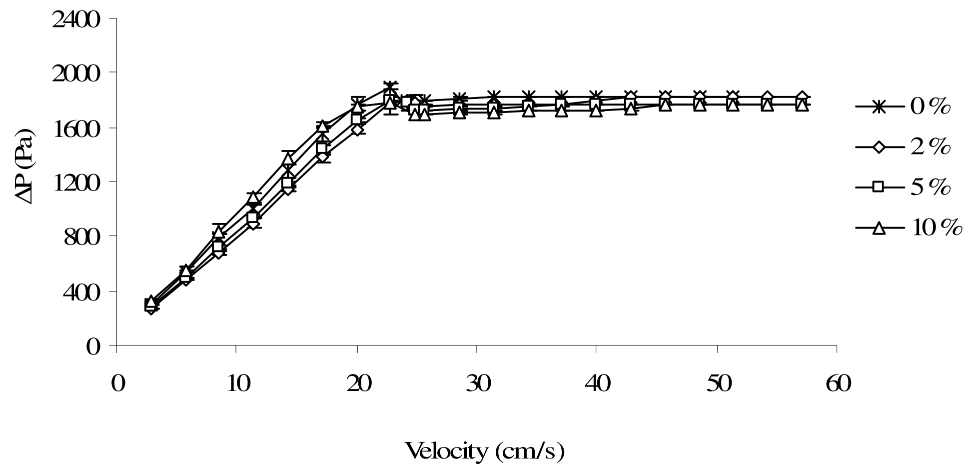


Figure 5.23 Fluidization of Hazelnut Shell-Silica Sand (595-850 μm) Mixtures with 2%, 5% and 10% Mass Percent of Hazelnut Shell

Minimum fluidization velocities for the mixtures of hazelnut shell and silica sand for different mass fractions and silica sand particle sizes are given in Figure 5.24. Mass fraction changes do not affect the minimum fluidization velocity. Low resistance of hazelnut shell particles to mixing and relatively higher density of hazelnut shell resulted in very well fluidization with silica sand.

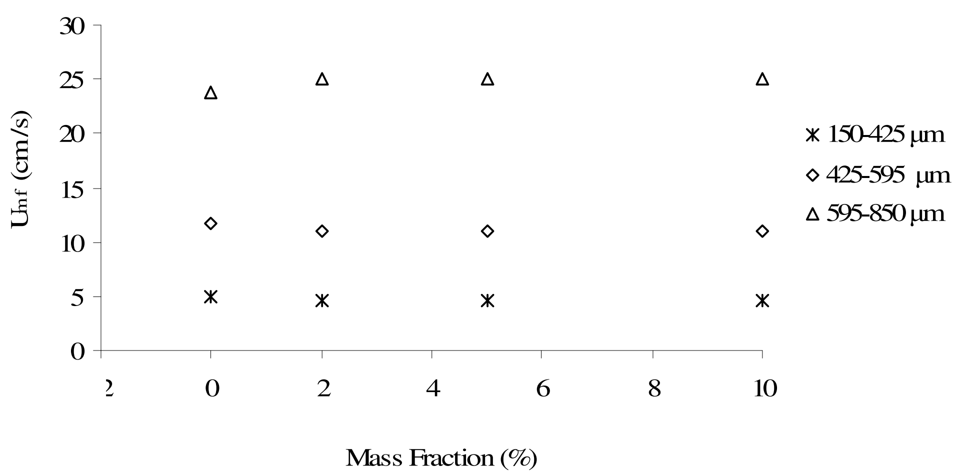


Figure 5.24 Effect of Mass Fraction of Hazelnut Shell in the Mixture on the Minimum Fluidization Velocity

5.2 Comparisons of the Experimental Results with Correlations Available in the Literature for Minimum Fluidization Velocity of Binary Mixtures

Correlations for minimum fluidization velocity of binary mixtures were introduced in Chapter 3. They mostly based on size, density, shape and fraction of components in the mixture. They are all empirical correlations. Some of them predict minimum fluidization velocities for binary mixtures of biomass-sand and others binary mixtures with components varying in size, shape and density. Comparisons of the results obtained by this study with the predictions of mentioned correlations are presented in this section.

5.2.1 Comparison of the Results for Rice Husk-Silica Sand Mixtures

Fluidization of rice husk is difficult due to its inappropriate physical properties. Mixing it with silica sand enables fluidization at lower velocities as shown in section 5.1. Volume fraction increase of rice husk creates resistance to fluidization. As being a low density material, mass fraction changes of rice husk in the mixture lead to large volume fraction changes and this bring about significant increase in minimum fluidization velocity of mixture. Figure 5.25 shows results of this study and prediction of correlations for mixtures of rice husk and silica sand (150-425 μm). For mass fraction content of 2%, all correlations predicted well but for the cases where mass fractions are 5% and 10%, no correlation have a good prediction. Figure 5.26 shows results for mixtures constituted by silica sand with particles size 425-595 μm. Again predictions of no equation fit experimental data of this study well.

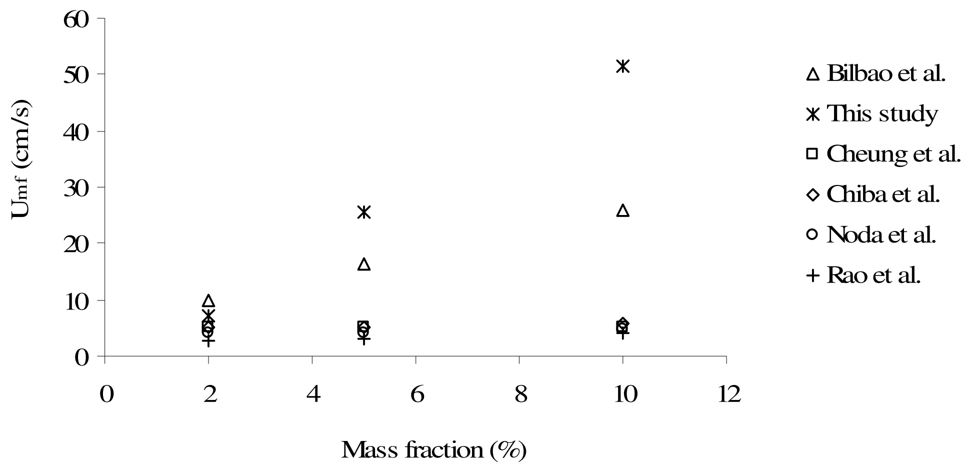


Figure 5.25 Comparisons of Minimum Fluidization Velocities for Rice Husk-Silica Sand (150-425 μm) Mixture

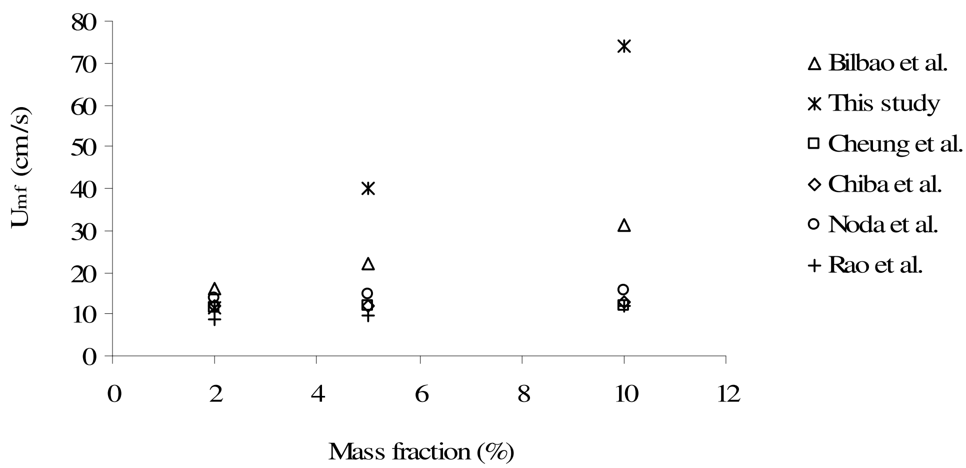


Figure 5.26 Comparisons of Minimum Fluidization Velocities for Rice Husk-Silica Sand (425-595 μm) Mixture

5.2.2 Comparison of the Results for Sawdust-Silica Sand Mixtures

Binary mixture of sawdust and silica sand exhibits well bubbling behavior. Mass fraction increase of sawdust lead to smaller increase in minimum fluidization velocity compared to rice husk. Figure 5.27 and 5.28 shows predictions of correlations and results of this study for two different types of silica sand. Equation of Bilbao et al. seems to have best predictions but still unsatisfactory for mixtures formed by silica sand with particle size150-425 μm. Predictions of Cheung et al. seems well for the mixtures formed by silica sand with particle size 425-595 μm.

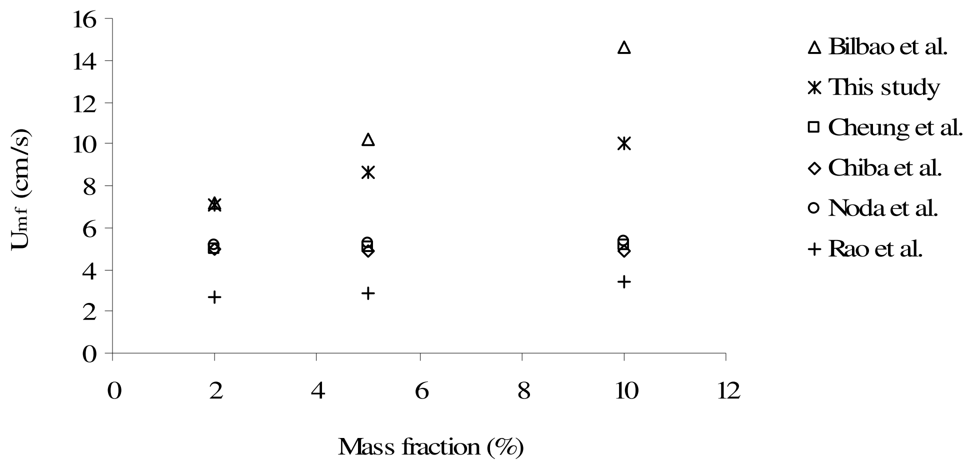


Figure 5.27 Comparisons of Minimum Fluidization Velocities for Sawdust-Silica Sand (150-425 μm) Mixture

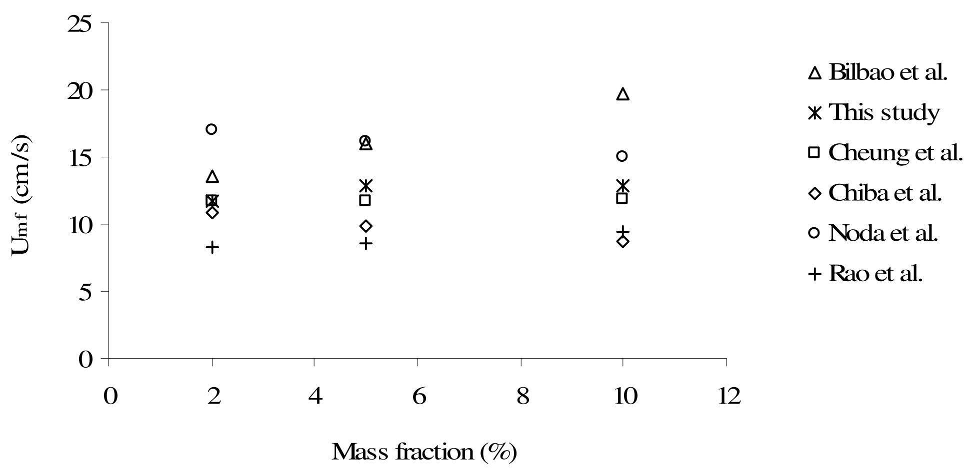


Figure 5.28 Comparisons of Minimum Fluidization Velocities for Sawdust-Silica Sand (425-595 μm) Mixture

5.2.3 Comparison of the Results for Wheat Straw-Silica Sand Mixtures

Mass fraction increase of wheat straw in the mixture resulted in rise of minimum fluidization velocity especially for 10% mass content as shown in Figure 5.29 and 5.30. Results for 2% and 5% mass fractions are close to each other but when mass percent of wheat straw in the mixture increased to 10%, minimum fluidization velocity was affected considerably. 10% mass fraction of wheat straw resists fluidization due to high volume fraction of it in the mixture. For the cases where mass fractions of wheat straw are 2% and 5%, all correlations predict the results of this study. But for 10% mass fraction, results of correlations are far from the result of this study. For low mass percentage of wheat straw, correlations of Chiba et al and Rao et al can be used to predict the minimum fluidization velocity of wheat straw-silica sand mixtures. Since pure wheat straw does not fluidize and equations of Cheung et al. requires the minimum fluidization velocity of wheat straw, this equation can not be used for estimating the minimum fluidization velocity of wheat straw-silica sand.

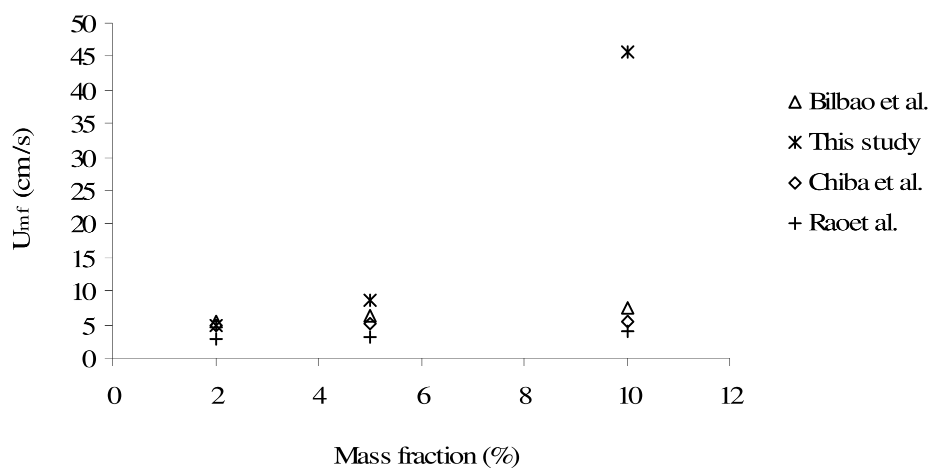


Figure 5.29 Comparisons of Minimum Fluidization Velocities for Wheat Straw-Silica Sand (150-425 μm) Mixture

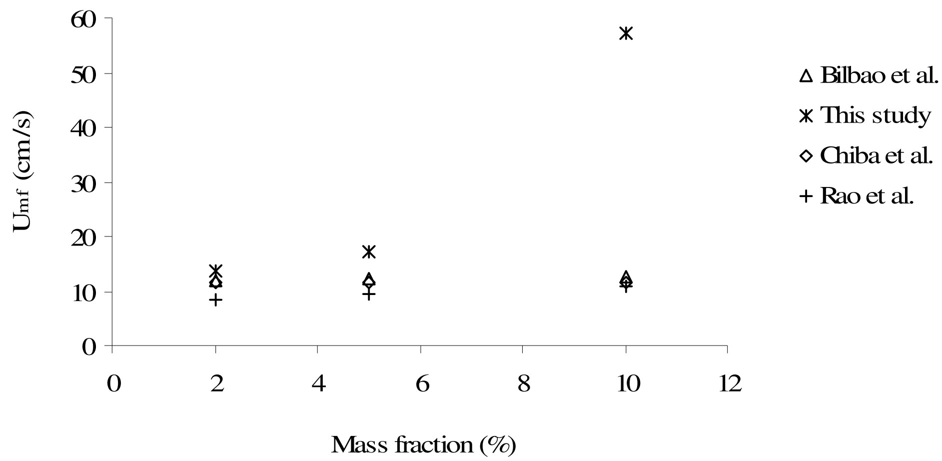


Figure 5.30 Comparisons of Minimum Fluidization Velocities for Wheat Straw-Silica Sand (425-595 μm) Mixture

5.2.4 Comparison of the Results for Olive Cake-Silica Sand Mixtures

Olive cake and silica sand forms a good combination due to easy fluidization of their mixture. Mass fraction increase of olive cake in the mixture does not have any effect on minimum fluidization velocity of the mixture as mentioned in section 5.1. Increase in sand particle size leads to increase in minimum fluidization velocity for the mixtures having same mass fraction of olive cake. Since mass fraction of olive cake did not affect the minimum fluidization velocity, experiments were carried out for the mixtures having silica sand with particle size of 595-850 μm to see the effect of silica sand particle size on minimum fluidization velocity in a wider range. Figures 5.31, 5.32 and 5.33 show the comparison results for three different type of silica sand. Correlations of Cheung et al. and Chiba et al. are very successful to predict all results of this study as can be inferred from the figures.

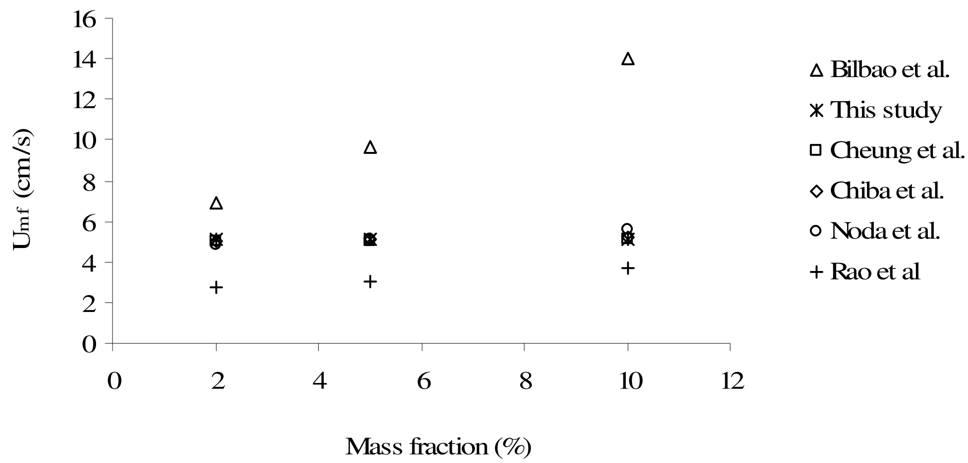


Figure 5.31 Comparisons of Minimum Fluidization Velocities for Olive Cake-Silica Sand (150-425 μm) Mixture

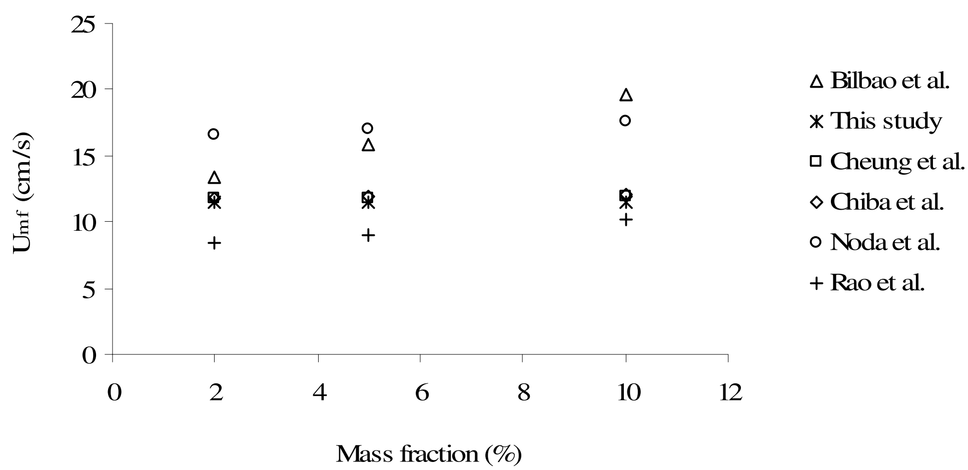


Figure 5.32 Comparisons of Minimum Fluidization Velocities for Olive Cake-Silica Sand (425-595 μm) Mixture

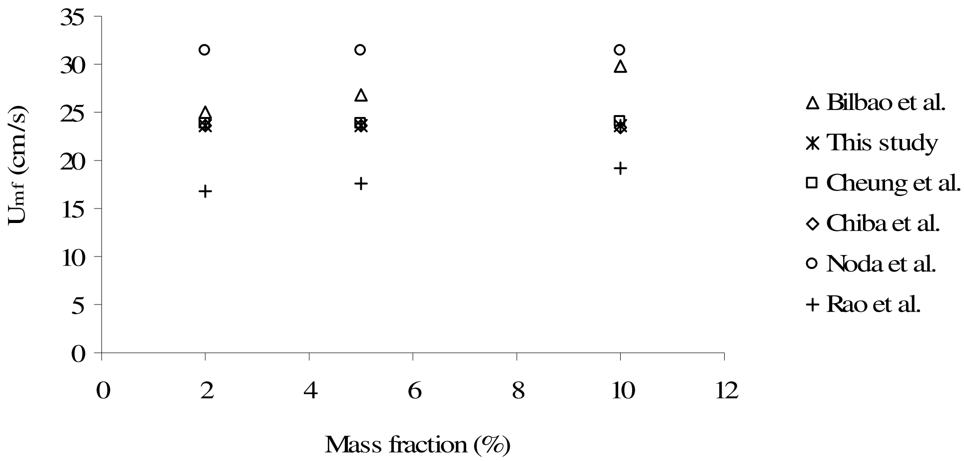


Figure 5.33 Comparisons of Minimum Fluidization Velocities for Olive Cake-Silica Sand (595-850 μm) Mixture

5.2.5 Comparison of the Results for Hazelnut Shell-Silica Sand Mixtures

Although hazelnut shell has inappropriate shape for fluidization, mixture of it with silica sand shows very well fluidization properties. Extra experiments for mixtures having silica sand with particle size of 595-850 μm were carried out for the same reason expressed for olive cake in the previous section. For mass fractions 2%, 5% and 10% of hazelnut shell, no change was observed in minimum fluidization velocities. Increase in silica sand particle size results in increase in minimum fluidization velocities for the same mass fractions of hazelnut shell. Equations of Cheung et al. and Bilbao et al. can not be used to predict the minimum fluidization velocities of mixtures of hazelnut shell-silica sand for the same reason expressed of wheat straw. Results of this study fit to predictions of Chiba et al. well and it is advisable to use this equation for the mixtures of hazelnut shell-silica sand.

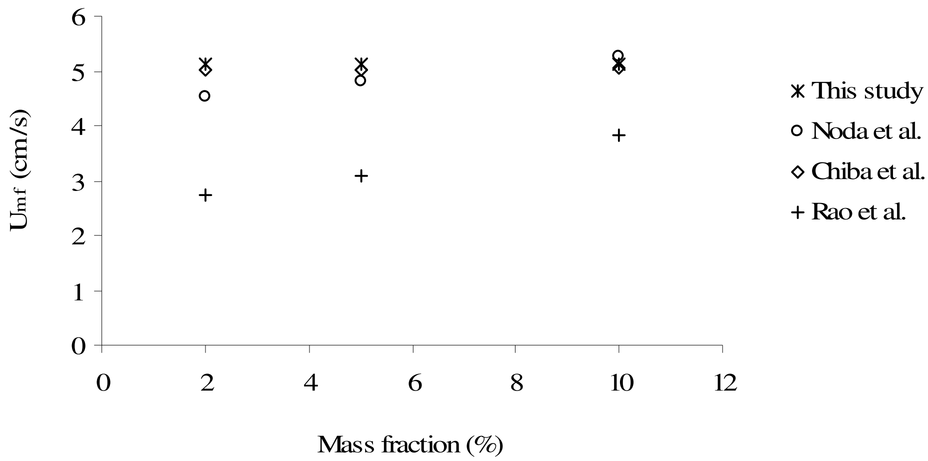


Figure 5.34 Comparisons of Minimum Fluidization Velocities for Hazelnut Shell-Silica Sand (150-425 μm) Mixture

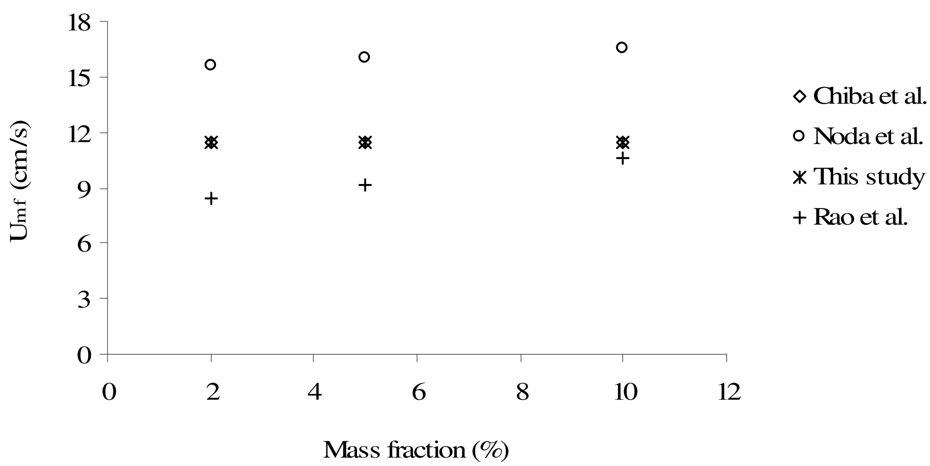


Figure 5.35 Comparisons of Minimum Fluidization Velocities for Hazelnut Shell-Silica Sand (425-595 μm) Mixture

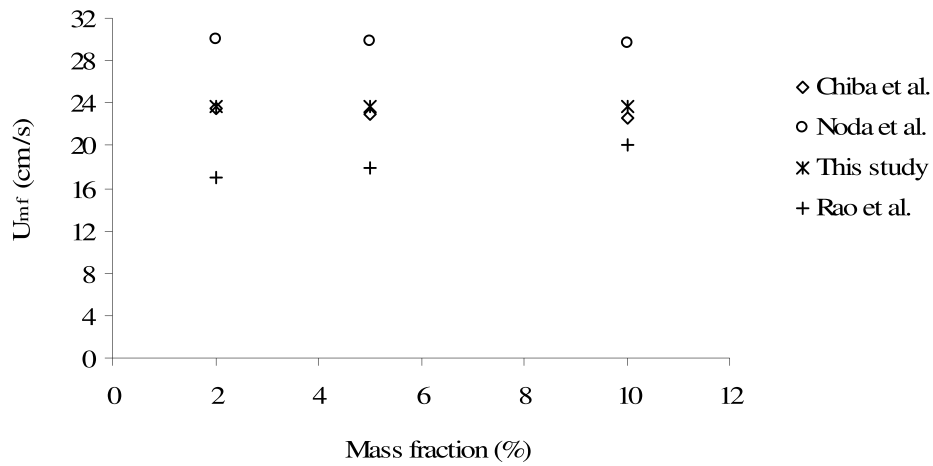


Figure 5.36 Comparisons of Minimum Fluidization Velocities for Hazelnut Shell-Silica Sand (595-850 μm) Mixture

5.3 Solid Mixing Behavior of Biomass-Silica Sand Binary Mixtures

This section of this study aims to investigate the mixing characteristics of biomass and silica sand mixtures in a bubbling fluidized bed. Five different biomass materials were employed to form binary mixtures with silica sand. Each of the biomass materials vary in their shape, size and density. As shown in coming sections, their peculiar physical properties result in different mixing behavior in a fluidized bed.

5.3.1 Rice Husk – Silica Sand Mixing Characteristics

In mixing experiments, the mixing time-time it takes to shut the air supply off- is an important parameter affecting the mixing behavior and the determination of this time is a crucial factor. Prior to the experiments those were conducted after bed reached steady state conditions, time dependent mixing behavior of rice husk particles was investigated. Figure 5.37 shows vertical distribution of rice husk in the bed at different times after bed was fluidized. These experiments were performed with the same method mentioned for mixing experiments. As can be seen from the figure, bed reaches steady state conditions at about 15 seconds after fluidization. Therefore, mixing pattern does not change after that point. In the light of these results, the mixing time was set as 5 minutes in all experiments to guarantee steady state operation. Y-axis of the figures which show steady state vertical distribution of biomass gives mixing index. This enables to evaluate mixing quality at each layer.

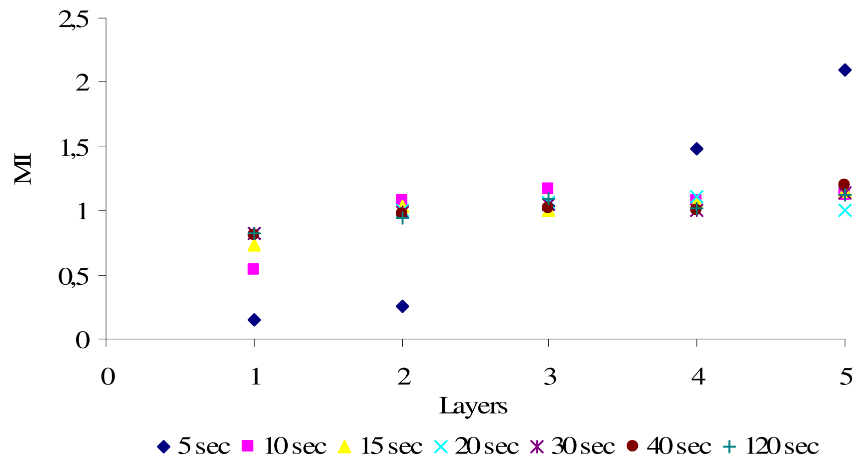


Figure 5.37 Time Dependent Vertical Distribution of Mass Fraction of Rice Husk in the Mixture of Rice Husk – Silica Sand (Silica Sand 150-425 μm)

Figure 5.38 shows the vertical distribution of rice husk along the bed for steady state conditions. Rice husk behaved like flotsam due to its much lower bulk density compared to silica sand. Rice husk mass fraction tends to increase with bed height. This situation is valid for all mixture loadings. Silica sand particles, as expected, accumulate mostly at the bottom of the bed. Bubbling was observed for all mixtures.

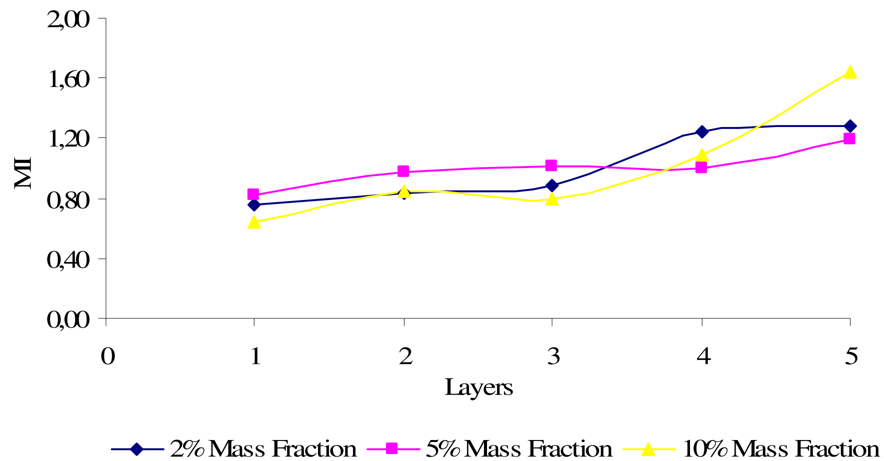


Figure 5.38 Vertical Distribution of Mass Fraction of Rice Husk in the Mixture of Rice Husk – Silica Sand (Silica Sand 150-425 μm)

Figure 5.39 shows the results for mixtures formed by silica sand that has a particle size 425-595 μm. Mixtures constituted by silica sand having particle size 425-595 μm have nearly the same mixing behavior as the previous one. This shows that silica sand particle size does not affect the mixing in the bed noticeably.

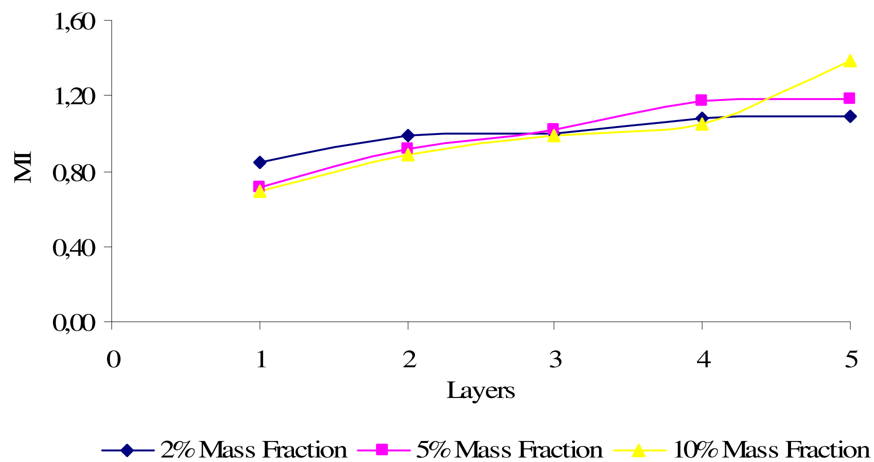


Figure 5.39 Vertical Distribution of Mass Fraction of Rice Husk in the Mixture of Rice Husk – Silica Sand (Silica Sand 425-595 μm)

5.3.2 Wheat Straw – Silica Sand Mixing Characteristics

Due to its lower density (100 kg/m^3) than silica sand, wheat straw acts as flotsam during fluidization similar to rice husk. Wheat straw was separated from silica sand by sieving and then corresponding mass of each component were determined by weighing. Figure 5.40 shows variation of the mass fraction of wheat straw in the binary mixture with mixing time. After 40 seconds from the beginning of fluidization, mixture reaches steady state conditions. In all experiments for wheat straw, mixing time was set as 5 min to guarantee steady state operation.

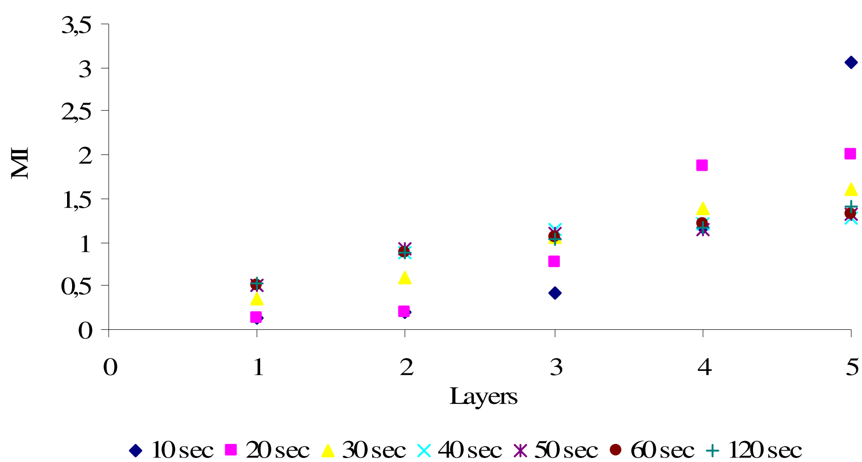


Figure 5.40 Time Dependent Vertical Distribution of Mass Fraction of Wheat Straw in the Mixture of Wheat Straw– Silica Sand (Silica Sand 150-425 µm)

Figure 5.41 shows steady state vertical wheat straw distribution for mixtures constituted by wheat straw and silica sand that has particle size 150-425 µm. For all cases wheat straw mass fraction increases with bed height. Bubbling was observed for all mixtures. The same trends are observed when coarse sand is used in the binary mixture as shown in Figure 5.42. Therefore, similar to rice husk, it can be suggested that the silica sand particle size has no significant effect on the mixing behavior of wheat straw and silica sand. Mixing quality of rice husk seems better since values of mixing index at each layer are closer to one as compared with mixing index of wheat straw at each layer.

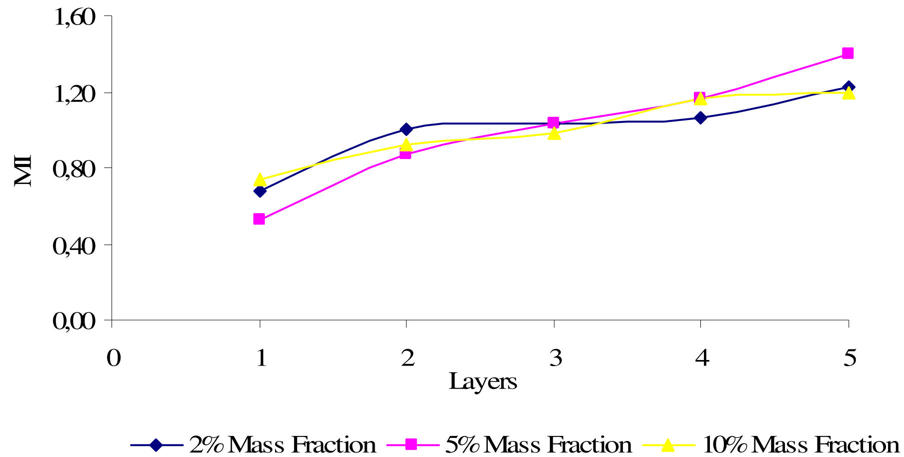


Figure 5.41 Vertical Distribution of Mass Fraction of Wheat Straw in the Mixture of Wheat Straw - Silica Sand (Silica Sand 150-425 μm)

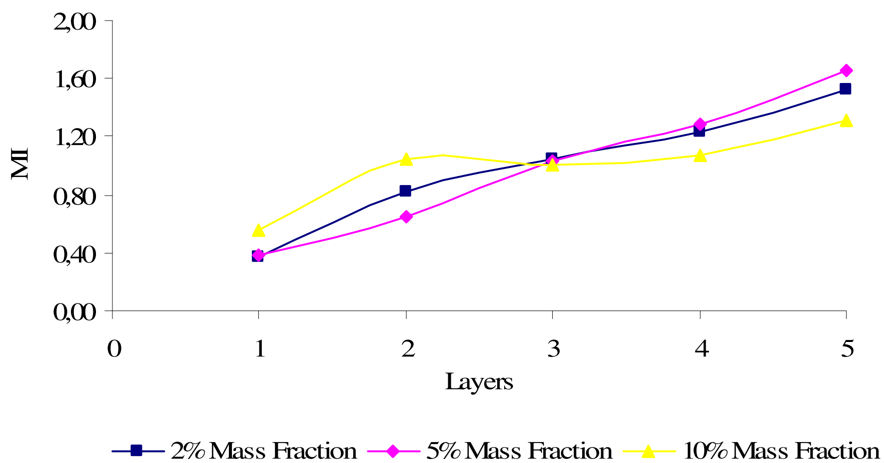


Figure 5.42 Vertical Distribution of Mass Fraction of Wheat Straw in the Mixture of Wheat Straw – Silica Sand (Silica Sand 425-595 μm)

5.3.3 Sawdust – Silica Sand Mixing Characteristics

Shape of sawdust particles is more spherical and mixture of sawdust-silica sand has better fluidization properties than mixtures constituted by other rice husk and wheat straw as can be inferred from fluidization curves given in section 5.1. Figure 5.43 shows the variation of the mass fraction of sawdust with height. Since the density of sawdust is lower than silica sand, it acts as flotsam and accumulates mostly at the top of the bed. Larger gradients for mixing index occur at the bottom and top regions. Mixing index at layers 1 and 5 are far from one and this denotes undesired mixing quality at these layers.

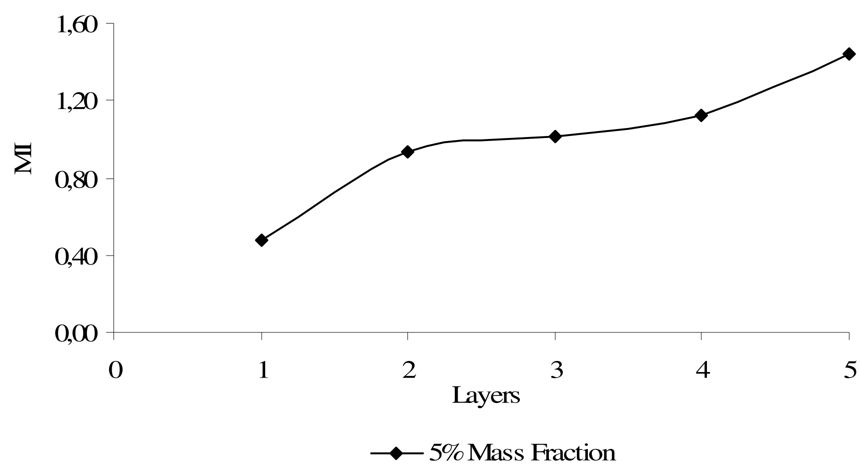


Figure 5.43 Vertical Distribution of Mass Fraction of Sawdust in the Mixture of Sawdust – Silica Sand (Silica Sand 150-425 μm)

Separation of sawdust from sand mixture is a difficult task to overcome. Burning sawdust after separated big sawdust particles by sieving seems to be the only possible way to separate it from silica sand considering the available equipments in the laboratory. To determine the correctness of the method, known amounts from each component was mixed and then separated from each other by mentioned method prior to the experiments. Error in the results was found within the range of

5-15%. Experiment was conducted only for the case where mass fraction of sawdust in the mixture is 5% silica sand with particle size was 150-425 μm due to separation difficulties.

5.3.4 Olive Cake – Silica Sand Mixing Characteristics

Although olive cake has the highest bulk density among biomass materials utilized in this study, its bulk density is still lower than that of silica sand. This leaded to increase in mass fraction of olive cake as going from bottom to top of the bed. Figure 5.44 shows the variation of the mixing index of olive cake with height. Mixing index for layers 1, 2 and 3 does not differ very much and they are close to one but there is a gradual increase beyond layer 3.

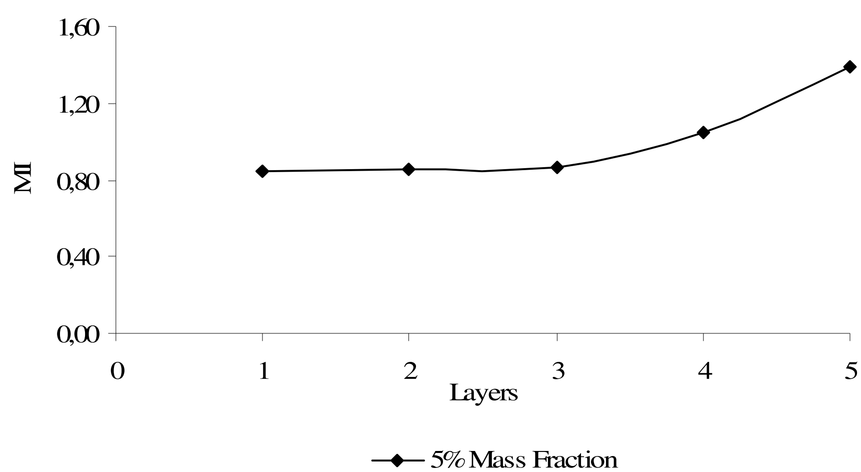


Figure 4.44 Vertical Distribution of Mass Fraction of Olive Cake in the Mixture of Olive Cake – Silica Sand (Silica Sand 150-425 μm)

Since the separation of olive cake and silica sand could only be achieved by the method same with sawdust and this requires much more effort than sieving, an experiment was carried out only for the case where the mass fraction of olive cake was 5% and silica sand with particle size was 150-425 μm.

5.3.5 Hazelnut Shell – Silica Sand Mixing Characteristics

Shape of hazelnut shell used in this study does not allow fluidization. Mixture of it with silica sand shows very well fluidization behavior. Good mixing of hazelnut shell and silica sand is also desirable for proper bed operation. Time dependent vertical distribution of hazelnut shell particles is given in the figure 5.45. It takes about 30 seconds for the mixture to reach steady state conditions after fluidization starts.

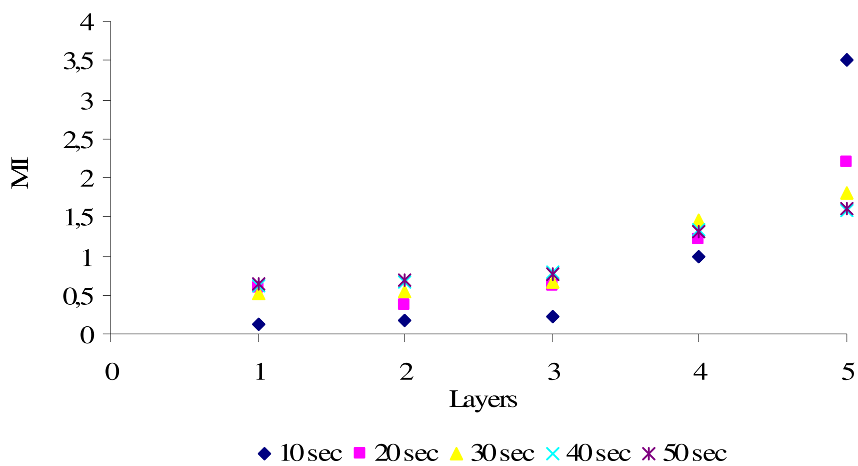


Figure 5.45 Time Dependent Vertical Distribution of Hazelnut Shell in the Mixture of Hazelnut Shell – Silica Sand (Silica Sand 150-425 μm)

As for the cases of other biomass materials, hazelnut shell has lower density than silica sand and its distribution along vertical direction of the bed is nearly same with others. The mass fraction of hazelnut shell increases with bed height. Figure 5.46 shows steady state vertical hazelnut shell distribution for mixtures constituted by hazelnut shell and silica sand that has particle size 150-425 μm. Although mixtures with different mass fractions have different mixing pattern in layers 2, 3 and 4, hazelnut shell particles tend to accumulate at the top region for all mixture types.

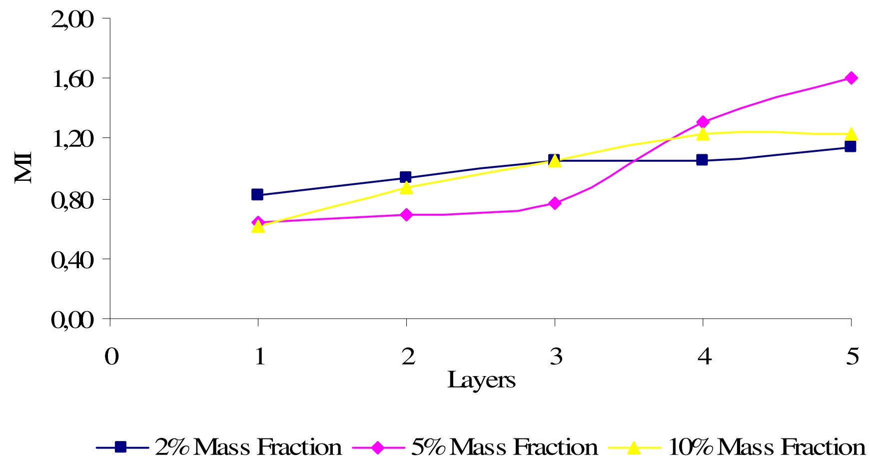


Figure 5.46 Vertical Distribution of Mass Fraction of Hazelnut Shell in the Mixture of Hazelnut Shell – Silica Sand (Silica Sand 150-425 µm)

Experiment for 5% mass content of hazelnut shell was carried out for the case hazelnut shell composes mixture with silica sand (425-595 µm). As can be seen from Figure 5.47 the silica sand particle size has almost no significant effect on mixing characteristics of hazelnut shell.

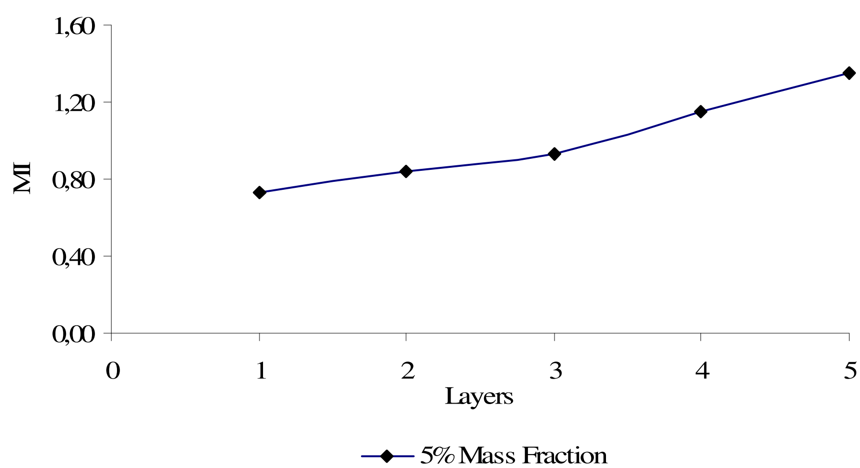


Figure 5.47 Vertical Distribution of Mass Fraction of Hazelnut Shell in the Mixture of Hazelnut Shell – Silica Sand (Silica Sand 425-595 µm)

5.4 Fluidization and Bubbling Characteristics of Sand-Biomass Mixtures in a 2-D Bed

Gas fluidized beds are widely used as gas-solid contactors in industrial applications such as drying of particles, combustion, catalytic cracking, calcining and mixing because of various advantages. These include rapid mixing of solids which lead to isothermal conditions in the reactor, and very high heat and mass transfer rates between gas and particles when compared with other modes of contact. The formation and presence of bubbles when the operating velocity exceeds the minimum fluidization velocity are responsible are these superior characteristics of fluidized beds. The rising bubbles expand the bed, drive the particle and gas circulation, and have a significant impact on the heat and mass transfer. It is the stirring action of the bubbles which is responsible for the good solids mixing and isothermal conditions [34].

Beside its advantages, bubbles may create adverse effects on bed operation. Large bubbles in a fluidized bed combustor may create blanketing effect on the heat transfer tubes and decrease heat transfer rate from bed to fluid inside tubes. They cause less gas solid contact leading to slow rates of combustion in the bed. Bursting of large bubbles at the bed surface may result in elutriation of particles or erosion of heat transfer tubes.

This part of the study attempts to investigate the fluidization and bubbling characteristics of biomass-silica sand mixtures in a 2-D bubbling fluidized bed. Images taken during fluidization of mixtures are presented as visual tools to observe the bed hydrodynamics.

5.4.1 Silica Sand Bubbling Behavior

Silica sand used for experiments in this part has density of 2600 kg/m^3 and particle size of 150-425 μm. It is included in Group-B of Geldart's classification of particles that have desirable properties for fluidization. Figure 5.48 shows the bubbles formed in the bed at three different velocities. Increase in superficial gas velocity promoted bubble size and bed expansion increase. The bed exhibits a typical bubbling behavior for all three velocities as expected for Geldart's group B particles.

(a) (b) (c)

Figure 5.48 Bubbling Behavior of Silica Sand (150-425 μm)

(a) U_0/U_{mf}=1.5 (b) U_0/U_{mf}=2.0 (c) U_0/U_{mf}=2.5

5.4.2 Rice Husk-Silica Sand Fluidization Behavior

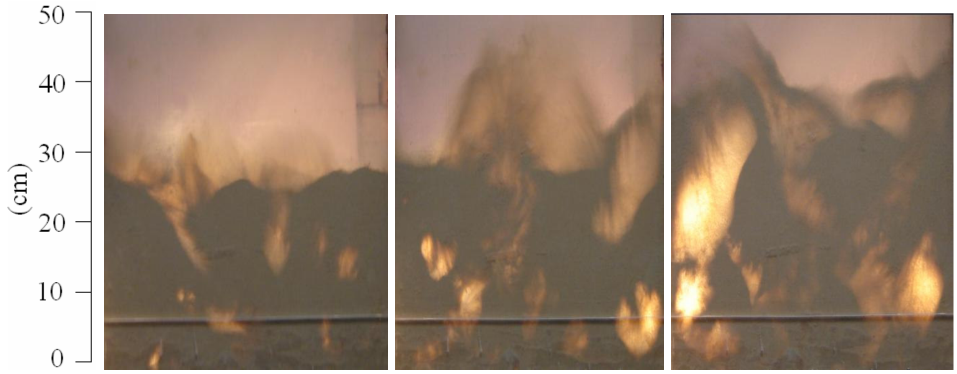
Prior to the experiments of rice husk-silica sand mixtures, pure rice husk was fluidized. Figure 5.49 shows rice husk fluidization characteristics. At low velocities, channel formation was observed in the bed. As the gas velocity increased and fluidization was achieved, turbulent-like flow appeared in the bed. Channel formation of rice husk can also be inferred from fluidization curve of rice husk given in section 4.1.

(a) (b)

Figure 5.49 Fluidization Behavior of Rice Husk in a 2-D Bed

(a) Before Fluidization (b) U_0/U_{mf}=1.2

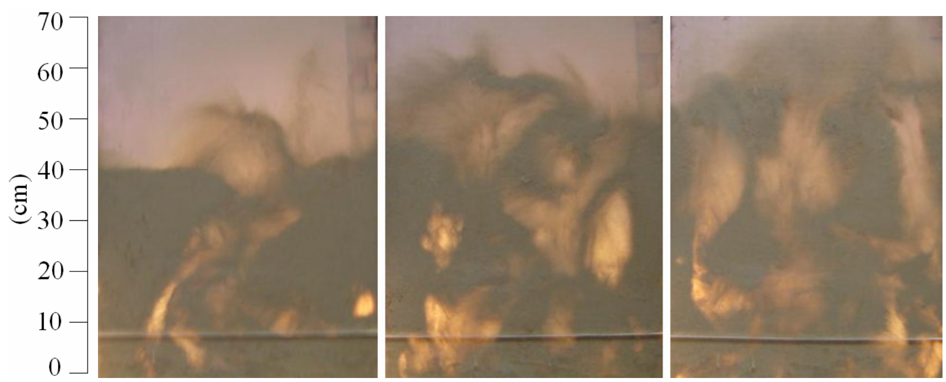
Rice husk-silica sand mixtures were fluidized for 2%, 5% and 10% of rice husk mass fraction contents. Fluidization becomes much easier and minimum fluidization velocity decreases significantly when rice husk was mixed with silica sand. Bubbling behavior was observed for mixtures instead of turbulent-like fluidization that was observed for pure rice husk fluidization as can bee seen from Figures 4.50-4.52. For each mixture, increasing in fluidizing gas velocity resulted in larger bed expansion and larger bubble size. Increase in rice husk mass fraction raised bed expansion noticeably due to increase in necessary minimum fluidization velocity. Experiment for the mixture with 10% rice husk content could not be conducted for U/U_{mf} = 2.5 since the bed height was not sufficient for appropriate observation.



(a) (b) (c)

Figure 5.50 Bubbling Behavior of Rice Husk-Silica Sand (150-425 µm) Mixture with 2% Mass Fraction of Rice Husk

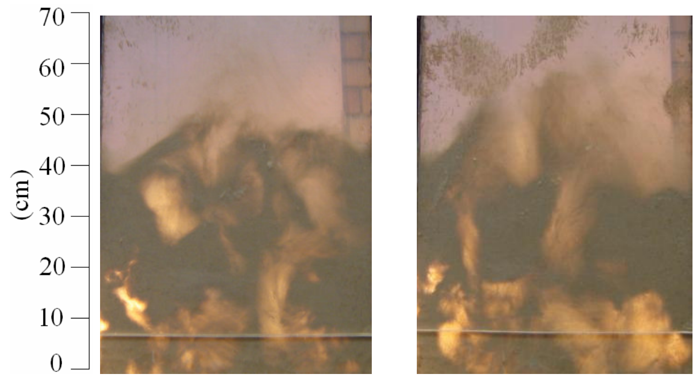
(a) U_0/U_{mf}=1.5 (b) U_0/U_{mf}=2.0 (c) U_0/U_{mf}=2.5



(a) (b) (c)

Figure 5.51 Bubbling Behavior of Rice Husk-Silica Sand (150-425 µm) Mixture with 5% Mass Fraction of Rice Husk

(a) U_0/U_{mf}=1.5 (b) U_0/U_{mf}=2.0 (c) U_0/U_{mf}=2.5



(a) (b)

Figure 5.52 Bubbling Behavior of Rice Husk-Silica Sand (150-425 μm) Mixture with 10% Mass Fraction of Rice Husk

(a) U_0/U_{mf}=1.5 (b) U_0/U_{mf}=2.0

5.4.3 Sawdust-Silica Sand Fluidization Behavior

Sawdust exhibits good fluidization behavior with silica sand although pure sawdust can not be fluidized properly. Figure 5.53 shows images taken for pure sawdust fluidization for three different velocities. Channels especially in the middle region of the bed affect fluidization adversely. At U_0/U_{mf} =1.5, channels more than one forms in the middle region. As velocity increased to U_0/U_{mf}=2.0 and U_0/U_{mf} =2.5 channels coalescence and one big channel covering about half of the bed appear in the middle of the bed. This is undesirable for bed operation since channeling decreases particle circulation, mixing rates and gas-solid contact.

(a) (b) (c)

Figure 5.53 Bubbling Behavior of Sawdust

(a) U_0/U_{mf}=1.5 (b) U_0/U_{mf}=2.0 (c) U_0/U_{mf}=2.5

Minimum fluidization velocity of sawdust decreases noticeably when it forms mixture with silica sand as shown in section 5.1. Since sawdust particles have higher sphericity compared to other biomass investigated in this work, their mixture with silica sand particles do not create much resistance for fluidization. Bubbling characteristics of sawdust-silica sand binary mixture were good. As in the case of other biomass materials, increase in superficial gas velocity and mass fraction of sawdust in the mixture result in bed expansion and larger bubbles as can be seen from Figures 5.54-5.56.

(a) (b) (c)

Figure 5.54 Bubbling Behavior of Sawdust-Silica Sand (150-425 μm) Mixture with 2% Mass Fraction of Sawdust

(a) U_0/U_{mf}=1.5 (b) U_0/U_{mf}=2.0 (c) U_0/U_{mf}=2.5

(a) (b) (c)

Figure 5.55 Bubbling Behavior of Sawdust-Silica Sand (150-425 μm) Mixture with 5% Mass Fraction of Sawdust

(a) U_0/U_{mf}=1.5 (b) U_0/U_{mf}=2.0 (c) U_0/U_{mf}=2.5

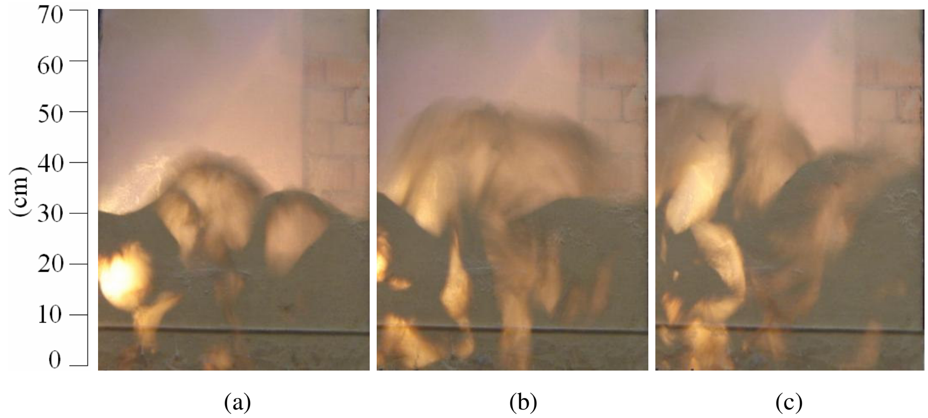


Figure 5.56 Bubbling Behavior of Sawdust-Silica Sand (150-425 μm) Mixture with 10% Mass Fraction of Sawdust

(a) U_0/U_{mf}=1.5 (b) U_0/U_{mf}=2.0 (c) U_0/U_{mf}=2.5

5.4.4 Wheat Straw-Silica Sand Fluidization Behavior

Pure what straw can not be fluidized. It shows piston-like behavior. Mixing of it with silica sand enables its fluidization. Mass fraction increase of wheat straw causes significant increase in minimum fluidization velocity especially for mixture with 10% mass fraction of wheat straw as shown in section 5.1. This situation leads larger bed expansion for mixtures with higher mass fraction compared to mixtures with low mass fraction for the same U_0/U_{mf} ratios as can be inferred from Figures 5.57-5.59. Larger bubbles form as mass fraction of wheat straw increases in the mixture. Experiment for the mixture with 10% wheat straw content could not be conducted for U/U_{mf} = 2.5 since the bed height was not sufficient for appropriate observation.

(a) (b) (c)

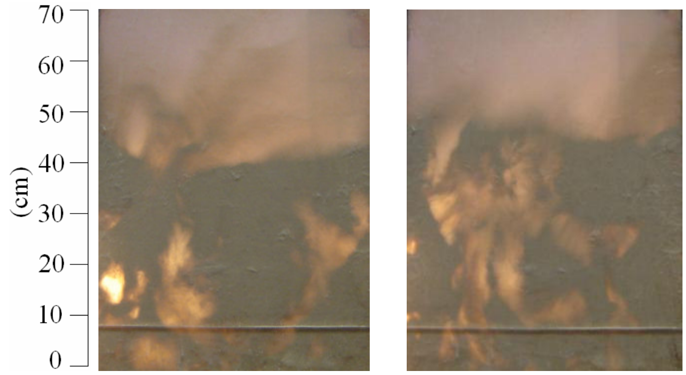
Figure 5.57 Bubbling Behavior of Wheat Straw-Silica Sand (150-425 μm) Mixture with 2% Mass Fraction of Wheat Straw

(a) U_0/U_{mf}=1.5 (b) U_0/U_{mf}=2.0 (c) U_0/U_{mf}=2.5

(a) (b) (c)

Figure 5.58 Bubbling Behavior of Wheat Straw-Silica Sand (150-425 μm) Mixture with 5% Mass Fraction of Wheat Straw

((a) U_0/U_{mf}=1.5 (b) U_0/U_{mf}=2.0 (c) U_0/U_{mf}=2.5



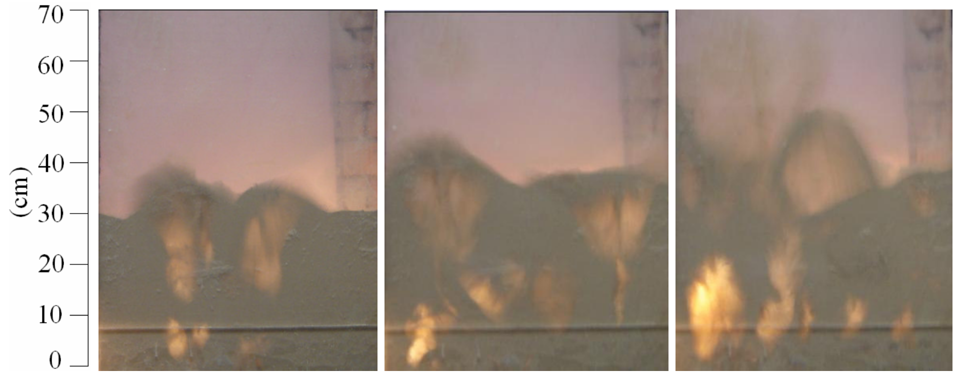
(a) (b)

Figure 5.59 Bubbling Behavior of Wheat Straw-Silica Sand (150-425 μm) Mixture with 10% Mass Fraction of Wheat Straw

(a) U_0/U_{mf} =1.5 (b) U_0/U_{mf} =2.0

5.4.5 Hazelnut Shell-Silica Sand Fluidization Behavior

Since hazelnut shell bulk density is relatively high compared to the rice husk, wheat straw and sawdust, its volume fraction is less than others for the same mass fraction. Lower volume fraction of biomass in the mixture leads to easier and better fluidization. Minimum fluidization velocity for mixture of hazelnut shell-silica sand mixture was found to be very close to that of silica sand only as shown in section 5.1. This proves that, hazelnut shell-silica sand mixture has desired fluidization characteristics. Figures 5.60-5.62 prove this situation. Desired bubbling bed was achieved for all mixtures.



(a) (b) (c)

Figure 5.60 Bubbling Behavior of Hazelnut Shell-Silica Sand (150-425 μm) Mixture with 2% Mass Fraction of Hazelnut Shell

(a) U_0/U_{mf}=1.5 (b) U_0/U_{mf}=2.0 (c) U_0/U_{mf}=2.5

(a) (b) (c)

Figure 5.61 Bubbling Behavior of Hazelnut Shell-Silica Sand (150-425 μm) Mixture with 5% Mass Fraction of Hazelnut Shell

(a) U_0/U_{mf}=1.5 (b) U_0/U_{mf}=2.0 (c) U_0/U_{mf}=2.5

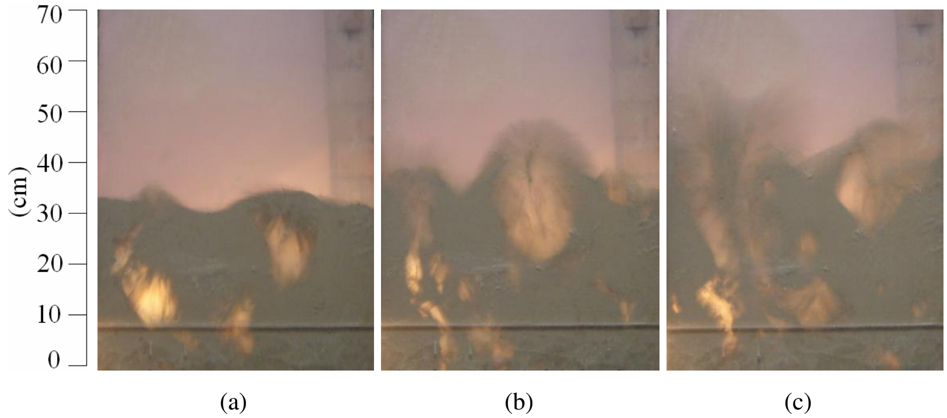
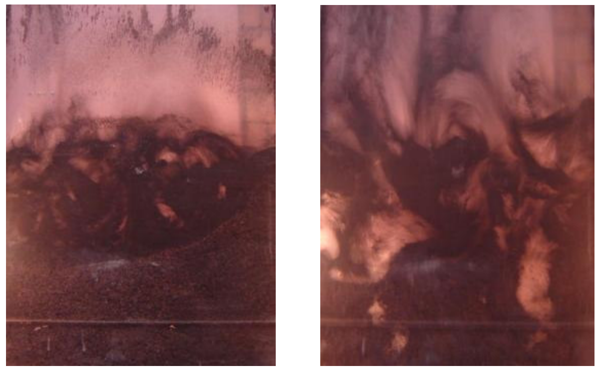


Figure 5.62 Bubbling Behavior of Hazelnut Shell-Silica Sand (150-425 μm) Mixture with 10% Mass Fraction of Hazelnut Shell

(a) U_0/U_{mf}=1.5 (b) U_0/U_{mf}=2.0 (c) U_0/U_{mf}=2.5

5.4.6 Olive Cake-Silica Sand Fluidization Behavior

Olive cake fluidization behavior is different than other biomass materials used in this study. Its particle size distribution was given in section 4.1 and as can be seen, very large and very fine particles are included in this material. Figure 5.63 shows the bubbling behavior of olive cake. At low gas velocities fine particles fluidize at the top of the bed and when the gas velocity exceeds the minimum fluidization velocity of larger particles, whole bed fluidizes. Since the velocity for complete fluidization of the bed is very high compared to the minimum fluidization velocity of fine particles, bed expands significantly at this velocity. Elutriation of fine particles from bed is highly possible for this situation.



(a) (b)

Figure 5.63 Bubbling Behavior of Olive Cake

(a) Fluidization of Only Fine Particles (b) Complete Fluidization

Olive cake-silica sand mixture has desired properties for fluidization. As determined in section 5.1, minimum fluidization velocities of the mixture are very close to that of silica sand. Resistance to fluidization of olive cake is low. Typical bubbling behavior was attained for olive cake-silica sand mixtures as can be seen from Figures 5.64-5.66. Minimum fluidization velocities and bubbling behaviors of olive cake-silica sand mixtures are very similar to that of pure silica sand.

(a) (b) (c)

Figure 5.64 Bubbling Behavior of Olive Cake-Silica Sand (150-425 μm) Mixture with 2% Mass Fraction of Olive Cake

(a) U_0/U_{mf}=1.5 (b) U_0/U_{mf}=2.0 (c) U_0/U_{mf}=2.5

(a) (b) (c)

Figure 5.65 Bubbling Behavior of Olive Cake -Silica Sand (150-425 μm) Mixture with 5% Mass Fraction of Olive Cake

(a) U_0/U_{mf}=1.5 (b) U_0/U_{mf}=2.0 (c) U_0/U_{mf}=2.5

(a) (b) (c)

Figure 5.66 Bubbling Behavior of Olive Cake -Silica Sand (150-425 μm) Mixture with 10% Mass Fraction of Olive Cake

(a) U_0/U_{mf}=1.5 (b) U_0/U_{mf}=2.0 (c) U_0/U_{mf}=2.5

CHAPTER-6

CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

6.1 Conclusion

Conclusions drawn in conjunction with the result of the experimental works of this study are presented below.

Mass percentage increase of rice husk, wheat straw and sawdust in the binary mixture of mentioned biomass and silica sand result in increase of minimum fluidization velocity of the mixture. Especially for rice husk-silica sand and wheat straw-silica sand mixtures, mass percentage increase of mentioned biomass materials leads to significant increase of the minimum fluidization velocity of the mixture. This point should be taken into consideration when designing fluidized bed gasifier or combustor for these biomass materials. Increase in fluidizing velocity causes increase in quantity of unburned carbon accumulating in cyclones and bag filters for fluidized bed combustors. Since residence time of particles in the bed reduces as the fluidizing velocity increases, this also increases CO emissions and affects adversely the combustion efficiency. As Natajaran et al. [35] emphasized, increase in fluidizing velocity for fluidized bed rice husk combustor increases the CO emissions and decreases the combustion efficiency. Change in fluidizing gas velocity cause different temperature distribution pattern in the bed. The temperature profile in the furnace has a strong influence on both CO emissions and combustion efficiency. If the superficial gas velocity is very high, a part of volatiles can be carried away in the flue gas that could result in reduction in combustion efficiency. Particles size of inert material (silica sand in this study) also has significant effect on minimum fluidization velocity. Increase in particle size of silica sand results in increase of minimum fluidization velocity of binary mixture of biomass-silica sand. If lower minimum fluidization velocity is desired for a fluidized bed unit, fine silica sand particles should be employed as bed inert material.

For a bubbling fluidized bed gasifier, equivalence ratio has important effects on bed operation. Equivalence ratio is defined as the ratio of actual air supplied per kg of fuel to stoichiometric quantity of air required for kg of fuel [35]. Minimum equivalence ratio is limited by heat supplied by partial burning of biomass to keep the bed at desired temperature and gas velocity to attain good fluidization in the bed. Upper limit for equivalence ratio is determined by fluidization quality of the bed material, elutriation of particles and bed operating temperature. To keep fluidizing gas velocity in the desired range depends highly on minimum fluidization velocity of the bed material. Increasing the mass percentage of biomass materials in the mixture of biomass-silica sand may require much more gas velocity to attain well fluidized bed as for the case of rice husk and wheat straw. This situation may lead to exceed desired equivalence ratio and to cause poor operation of the bed. Mixing of biomass particles in the bed is important to attain well temperature distribution in the unit. Operating the bed of biomass-silica sand binary mixture at about minimum fluidization velocity may result in poor mixing especially for mixtures having high mass percentage of biomass. All these cases should be taken into account during design stage of a fluidized bed unit.

All biomass materials used in this study have volatile matter content between 60% and 80%. This means that combustion of these volatile matters will be take place in the freeboard region and this increases the possibility of relatively higher temperatures in the freeboard region. Mixing and segregation experiments of the present study shows that biomass materials accumulate mostly at the top of the bed due to their lower density which may also promotes combustion of more biomass at the top of the bed and higher temperatures in this region. Secondary air injection may be required in the freeboard region for better combustion. As Varol and Atımtay [32] mentioned secondary air injection into the freeboard region of a bubbling fluidized bed combustor for olive cake has been a useful solution to decrease the CO and hydrocarbon emissions and to increase the combustion efficiency. Since biomass materials carry high volatile matter content within their constitutions, feeding point of these particles to a combustor or gasifier is crucial. Overbed feeding promotes burning of biomass in the freeboard region and this cause higher temperature in freeboard region. Feeding of biomass under the bed provides combustion of biomass in the bed material, more uniform temperature distribution in the bed and increase of combustion efficiency.

In section 5.2 of the present study, comparisons were carried out between the results of the experiments of present study and predictions of the correlations proposed for minimum fluidization velocity of binary mixtures. No correlation is able to predict the minimum fluidization velocities of rice husk-silica sand, wheat straw-silica sand and sawdust-silica sand mixtures well. Correlations of Cheung et al. [13], Chiba et al. [14] predict the results of olive cake-silica sand successfully. Only equation of Chiba et al. [14] predicts the minimum fluidization velocity of hazelnut shell-silica sand mixture well. These correlations can be used to predict the minimum fluidization velocity of the mentioned mixtures prior to design of a combustor or gasifier.

Images taken during steady state fluidization of mixtures in 2-D bed column at U_0 / U_{mf} =1.5, 2.0 and 2.5 are presented as visual guidance for fluidization and bubbling behavior of the bed. Pure sawdust, hazelnut shell, rice husk and wheat straw all have poor fluidization properties. Mixtures of mentioned biomass materials with silica sand result in improvement of their fluidization behavior. Good bubbling bed was obtained for all biomass-silica sand mixtures. Formation of uniform bubbles enhances the mixing and provides uniform temperature distribution in the bed. Channel formation and possible problems caused by channel formation is prevented.

6.2 Recommendations for Future Work

As mentioned in previous chapters, most of the biomass materials used in this study has poor fluidization properties. If pure biomass fluidization is desired for any thermochemical operation in a fluidized bed, some fluidization enhancement techniques may be employed for their better fluidization. Pulsation of fluidizing air or vibration of the bed may be beneficial to achieve better pure biomass fluidization.

In section 5.3, mixing and segregation behavior of the biomass-silica sand binary mixtures were investigated at steady state conditions for $U_0/Umf = 2$. Mixing and segregation behavior of the mentioned binary mixtures is affected by superficial gas velocity. Investigating the affect of superficial gas velocity on mixing and segregation behavior of the mixtures can be suggested for further research.

The experiments of the present study were carried out in cold model laboratory scaled bubbling fluidized bed columns. In real applications, combustion or gasification units differ in size and operating conditions. Scale up problems arise at that point. Hydrodynamic behavior of biomass-silica sand binary mixtures in a cold bed and in a hot bed may be different due to temperature difference and formation of ash, tar etc. Glicksman [36] developed some scaling laws that would enable a designer to do test his/her tests on a small model of a fluidized bed combustor at ambient temperature. The scale model cold bed would primarily aid in optimizing the fluid mechanical behavior of the bed. Bed geometry, particle size and density, and air velocity all greatly influence the fluid mechanics in the bed. Any of these variables could be easily modified using a model bed that has been constructed within the framework of Glicksman's scaling laws. Once the scaling laws have been verified, they can be used to construct small beds operating at ambient temperature which accurately model the fluid mechanical behavior of full scale hot beds [37]. Results of this study can be used in conjunction with results obtained from a hot bed to verify scale up parameters or to develop new parameters if needed.

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APPENDIX A

PHOTOGRAPHS OF BIMASS MATERIALS

Figure A-1 Photograph of Rice Husk

Figure A-2 Photograph of Wheat Straw

Figure A-3 Photograph of Sawdust

Figure A-4 Photograph of Olive Cake

Figure A-5 Photograph of Hazelnut Shell