International Journal of Engineering and Applied Science October 6 University
https://ijeasou.journals.ekb.eg/
Online ISSN 3009-6448
Volume (2),Issue(1)
January 2025, pp:160-166

Potential Research Works on Fluidized Bed Combustors

M. M. Kamal[1*]

1 Department of Mechatronics Engineering, Faculty of Engineering, October 6 University, 6th of October City, 12585, Giza, Egypt.

* Corresponding author's email: mkamal@eng.asu.edu.eg

https://doi.org/10.21608/ijeasou.2025.352787.1043

Received:13 January 2025
Accepted: 23 January 2025
Published: 23 January 2025

Abstract – The characteristics of the fluidized bed combustion are highlighted. The concept of fluidization is clarified and the corresponding flow features are illustrated in terms of what have been documented in the literature about such systems. The most relevant previous works have been documented either in the cold flow study area or in correspondence to the reactive flow aspects. Photos from preliminary works by the author are provided to visualize the cold flow and combustion characteristics of the fluidized bed in order to reveal the interesting features that set the potential for future works. The turbulence development and the subsequent impact on the combustion characteristics are explored in order to set the base for future research works that effectively serve the industrial community. In this regard, the recommendations for future works are provided at the end to provide the sustainability of the system upon involving more innovative designs and working scenarios of the fluidized bed combustors in the industrial field.

Keywords: Fluidized Bed, Turbulent Flow and Combustion, Biomass Devolatilization and Volatiles, Char Oxidation, Heat Transfer

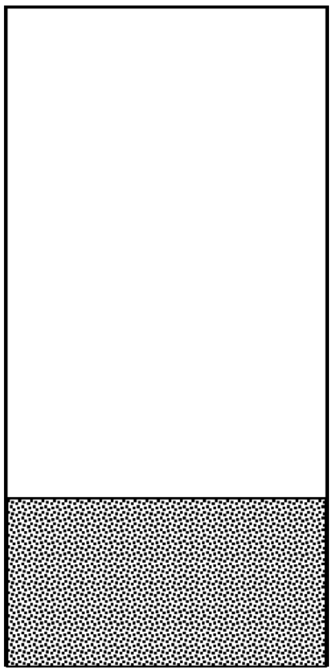
1. Introduction:

Fluidization is the phenomenon of having particulate materials which behave like a fluid or a frictionless continuum. Figure 1 shows how such a phenomenon takes place when a packed bed (Fig. 1a) becomes in the turbulent regime at which the particles are dispersed (Fig. 1b). Such phenomenon is commonly experienced in industrial processes for the purpose of enhancing the interaction between the solid (which is the discrete particulate phase) and the gas (which is the continuous phase). Such interaction is important during the stages of biomass combustion (Fig. 1c). Any solid biomass particle entering a combustor undergoes four distinct combustion stages: drying, devolatilization, combustion of gases, and char burning. Overlapping of these combustion stages may occur, when considering the combustion of a single particle. When a biomass particle is introduced to a hot environment the water in the particle starts to evaporate. During the devolatilization stage, volatile gases and tars are released from the particle and are combusted in the presence of oxygen. In the char combustion stage, the char reacts with oxygen to form mainly CO and CO_2. After the combustion is completed, an inorganic ash is left (Gómez-Barea and Leckner, 2010).

2. Methodology:

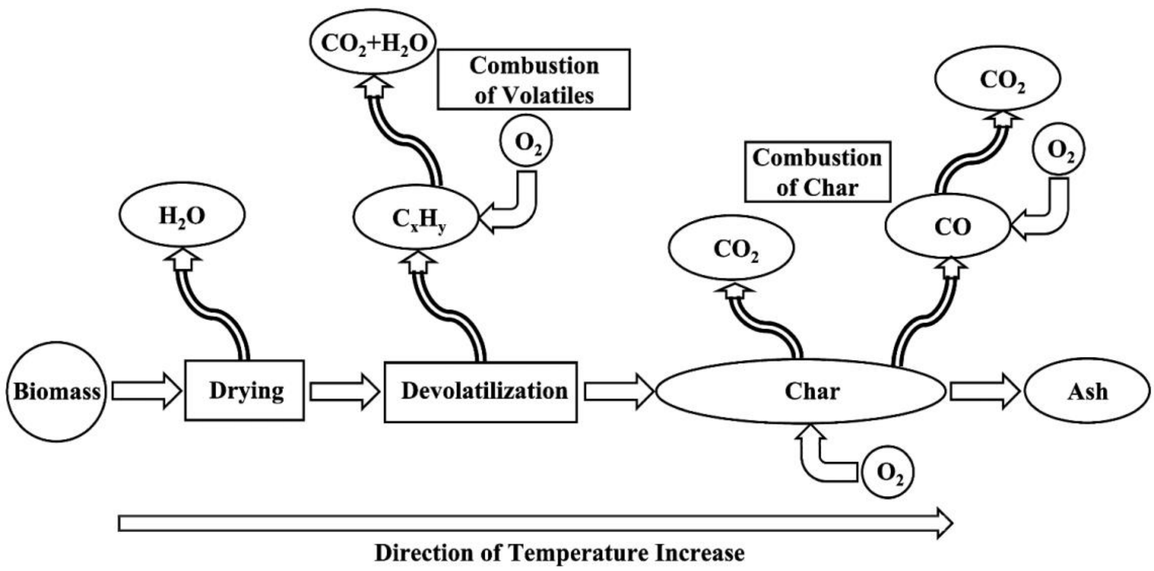
The minimum fluidization velocity is the superficial fluid velocity at which the fluid drag force balances the gravity force acting on the bed. The minimum fluidization velocity is significantly smaller than the terminal velocity of a single particle in an infinitely large fluid. Therefore, a particle blown out of the bed by bubble-bursting above the bed, just above minimum fluidization, returns to the bed, since its terminal velocity is too low for it to be carried out of the bed. This phenomenon is due to the fact that the friction coefficient is higher for a packed bed than for a bed of spheres that are very far apart. The higher the solid volume fraction, the greater the friction force becomes. Such change of resistance with the solid volume fraction gives rise to the oscillatory behavior of the fluidized bed which is responsible for many of the useful features of fluidized beds, such as the intensive heat and mass transfer rates. The primitive explanation is to found in such resistance behavior. In this regard, as the gas flows through the bed above the minimum fluidization velocity, the bed expands to minimize the resistance to flow. As the resistance becomes too low, the particles cannot be supported by the gas any longer and consequently, they drop down (Leckner, 2024). This process is repeated over and over again. Consequently, fluidization provides a range of operating flow rates within which the turbulent interaction between the gas and solid is satisfied (Okasha, 2016).

The cold flow features of fluidization can be revealed from the investigation on the sawdust fluidized bed (which can be potentially used for ensuring efficient combustion of biomass). The minimum fluidization velocity can be detected among the images in Fig. 2 (which show how the air velocity develops from a zero magnitude up to the condition of fluidization.



(a) Packed Bed

(b)Turbulent Regime



(c)

Fig. 1 Illustration of the Flow Pattern and Combustion Reactions inside the Fluidized Bed

(a)

(b)

(c)

(d)

(e)

(f)

(g)

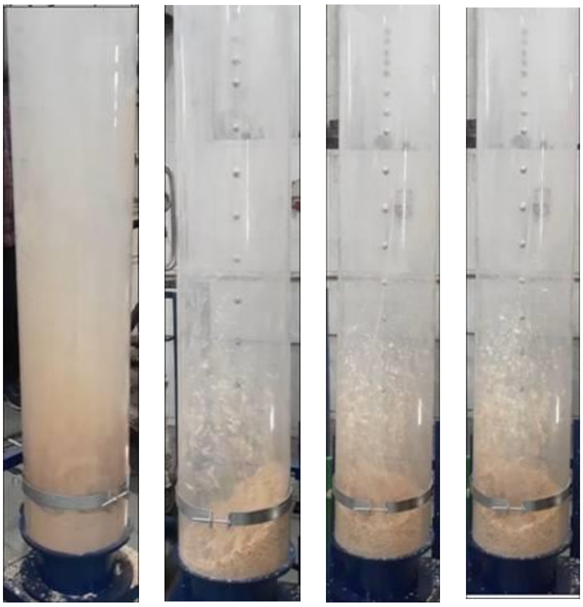
Fig. 2. Images for Fluidizing Sawdust Large Particles

Fig. 2h

Fig. 2i

In Fig. 2c and Fig. 2d, the particles are noticed to move upward in the available space above the bed. The bed expands further and further upon increasing the velocity under the conditions that are reached in Fig. 2e, Fig. 2f and Fig. 2g.The closer look at the individual paths of particles (Fig. 2h and Fig. 2i) indicates that the particles stay longer times inside the mixing chamber as the turbulence intensity increases. Figure 2 thus describes the significance of the air velocity development to achieve fluidization.

As the sawdust gets a finer particle size, the turbulent flow zone (Fig. 3a) becomes more homogenous in comparison to the cases of larger size particles (Fig. 3b, Fig. 3c and Fig. 3d).



(a) (b) (c) (d)

Fig 3. Images for Fluidizing Sawdust Fine Particles

3. Results and Discussion:

Due to shortage in the resources of the fossil fuel, there is an increasing need to focus more on the combustion of biomass. This makes the science of combustion more interesting for dealing with the complex kinetics of volatiles and char oxidation. In the same respect, the aerodynamics of fluidization is an active area for research which strengthens the linkage between combustion and turbulence. The co-combustion of biomass in large scale fluidized bed is utilized in the existing facilities (Bartels et al., 2008).

Kafle et al. (2014) stated that biomass combustion releases heat energy along with other components. A bubbling fluidized bed combustor (Fig. 4) can be potentially used for combusting the sawdust. If the flow velocity increases, a circulating fluidized bed is obtained and a cyclone separator has to be used.

The first challenge is to adjust in the feeding rate of the solid biomass via a reliable mechanism. The chemical reactions start during the stage of the biomass pyrolysis. When the surface region is heated to greater than 500 K, pyrolysis begins. Tu et al. (2017) reported the pyrolysis temperature ranges as follows: hemicelluioses, (500-600 K); cellulose, (600-650 K) and lignin, 500-773 K. As combustion proceeds, the NOx formation from different routes is experienced as a significant challenge. The flame temperature may have a minor influence on fuel NO formation under specific conditions (Riaza et al., 2014).

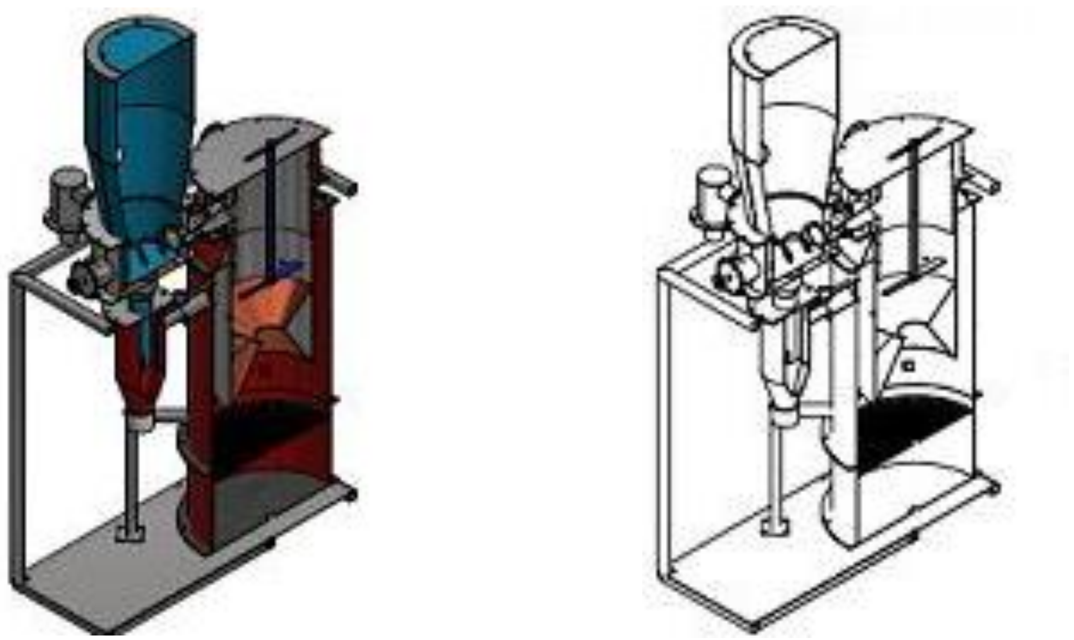


Fig. 4 Construction Details for a Bubbling Fluidized Bed

In detail, holocellulose pyrolysis begins with an attack on the glycosidic linkages between the individual glucose, xylose and arabinose (Chen et al, 2024). A series of reactions proceed and the molecules get into gaseous fragments and produce char via condensation reactions. Higher temperatures favor the volatile producing reactions, while lower temperatures favor the char production (Kamal, 2008 and Collazo et al., 2012). The gaseous products from the traditional pyrolysis include CO, CO_2, CH_4 and C_2H_6 in percentages of 50, 10, 38, and 2, respectively (Basu, 2013). The dominant influence of the moisture content is to reduce the flame temperature in the combustor, thus driving the products toward char with less rates of pyrolysis (Shen and Yoshikawa, 2013). The inert gases act as a heat sink, thus reducing the local temperatures and may act as a catalyst for char formation.

The char evolved by pyrolysis is quite porous and contains numerous free-radical sites for the attack of oxygen (Görabsson et al., 2011). As an active species for combustion, the concentration of CH_2O reaches its maximum in flames at 1320 K, well in the temperature range of wood combustion (Yu et al., 1997). For relatively low temperature processes (such as the range from 1270 to 1970 K) which may be reached during wood combustion, chain termination reactions occur in the secondary reaction region (Okasha, 2003).

It is worthy to indicate that in fluidized-bed combustion, all combustion reactions take place in the same zone. While the combustion of wood is less efficient than the combustion of coal, the rates of heat release are substantially higher. This results from the reactivity which is related to the higher volatile content of wood in comparison to coal. The proximate analyses of a wide range of wood fuels show an approximate volatile/fixed carbon ratio of 3:1 for most wood fuels (Abelha et al., 2003). This is different from the case of coal, where the ratio may be less than 1:1 (Demirbas, 2004). Wood is a more reactive fuel which is generally a sulfur-free fuel.

The quantity and form of fuel nitrogen both influence NOx formation (von Berg et al., 2023). The nitrogen is largely contained in amine functional groups, which are contained in the protein content of the inner bark (Okasha, 2007). Trace quantities of nitrogen are additionally contained in lignin precursors (Scala and Salatino, 2002). In contrast, nitrogen in coal is contained in amines, pyridines, carboyoles, quinolines, and pyrroles. Therefore, the nitrogen in the wood fuel is in a more accessible and reactive form. The amine functional groups are volatilized readily in the solid-phase pyrolysis zone.

Because a highly turbulent flow field is established by a fluidized bed, fluidized beds are extended to accommodate combustion of heavy liquid fuels (Okasha, 2003). There is a group of research which is devoted to the interaction between NOx and CO emissions. In this regard, it was stated that carbon monoxide in the fluidized bed reduces NO to the elemental nitrogen according to the following mechanism:

$$2CO + 2NO \rightarrow 2CO_2 + N_2$$

The qualitative features of the biomass can be indicated from Fig. 5, which show the combustion regions for wood chips whose paths can be clearly traced within the fluidized bed. It is noticed how the biomass feed follows the vortical flow paths of the combustion air stream (Fig. 5a). In addition, the biomass residence time is elongated by the flow intensive shearing such that the flame spectrum changes as a result of getting more intensive combustion (Xie et al., 2023).

(a) **(b)**

Fig.5.Images for Biomass Turbulent Combustion

4. Future Studies

Fluidized beds can be potentially combined to pulsating flows, swirling flows or flow impingement of opposing jets to elongate the contact time between the flow and the solid media. In addition, extension to the various biomass materials (which pronounce different pollution levels) can be accomplished. For instance, the agricultural crops and waste materials can be extended to include corn, soybeans, sugar cane, switchgrass, woody plants, algae, and crop and food processing residues.

The environmental impact can be pronounced in the reduction of the SOx emissions that arise due to the sulfur content in such materials. Various nozzle shapes such as the shapes with elliptical cross-sections and sharp corners in addition to variable combustor cross-sections may be employed in order to set the base for more innovative fluidized bed designs. In this regard, the nozzle shapes with the elliptical and sharp corners introduce favorable non-symmetrical flow strain rates around the jet. It follows that during the jet dispersion, axis switching occurs for the jet which increases the entrainment rates and the resultant turbulent kinetic energy. Likewise, the combustor variable cross-sections such as the cross-sections with a sudden expansion introduce corner-recirculation zones. Furthermore, the divergent cross-section assists the flame stabilization since the flame can be stabilized at the position wherein the flow velocity matches the local flame speed. More extensive CFD research work has to be done to address the turbulent length scales which are strongly coupled to the solid fuel combustion in the fluidized beds.

In this regard, direct numerical simulation should be employed to well describe the small scales and the large scales of turbulence. Acetone as a solvent can be used to facilitate ignition and combustion of the sawdust and other biomass materials. More experimental works can be devoted to utilizing the fluidized bed for solid fuel gasification. Finally, implementing the bluff body various geometries for the combustion of natural gas under highly aerodynamic flow field conditions is recommended. This is beneficial for extending the flame stability limits and enhancing the combustion efficiency of biomass via effective ways for implementing the co-firing techniques in future research. A final conclusion is that the fluidized beds have significance in providing a solution for the sustainable use of energy. In this regard, the industrial community faces large challenges in satisfying the energy demands upon only relying on fossil fuels. Utilizing the agricultural residues and waste materials contribute to the satisfaction of the energy needs as well as the establishment of carbon-free combustion. The integration of researches on turbulence and chemical kinetics provides the key factors for ensuring stable and efficient combustion of biomass in the fluidized beds.

References:

[1] M. Bartels, W. Lin, J. Nijenhuis, F. Kapteijn and J. R. Van Ommen, 2008. Agglomeration in fluidized beds at high temperatures: Mechanisms, detection and prevention. Progress in Energy and Combustion Science, 34, 633-666, 2008.

[2] S. Kafle, S. H. Euh, K. Oh and C. LaHoon, 2014. Reduction of tar in combustion of wood pellet using catalyst in the boiler, Conference: Korean Society of Agricultural Machinery (KSAM 2014) Autumn Conference, At: Cheonan, South Korea, Volume: 19.

[3] F. M. Okasha, 2003. The fluidized bed combustion of a heavy liquid fuel, Experimental Thermal and Fluid Science, 27, 473-480.

[4] F. M. Okasha, 2016. Short overview on the jetting-fountain fluidized bed (JFFB) combustor. Renewable and Sustainable Energy Reviews, 55, 2016, 674-686.

[5] Y. Tu, A. Zhou, M. Xu, W. Yang, B. Siah and S. Prabakaran, 2017. Experimental and numerical study on the combustion of a 32 MW wood-chip grate boiler with internal flow gas recirculation technology, Energy Procedia, 143, 591-598.

[6] M. M. Kamal, 2008. Parametric study of combined premixed and nonpremixed flame coal burner, Fuel, 87, 1515-1528.

[7] J. Riaza, R. Khatami, Y. A. Levendis, L. Álvarez, M. V. Gil, C. Pevida, F. Rubiera, J. J. Pis, 2014. Combustion of single biomass particles in air and oxy-fuel conditions, Biomass and Bioenergy, 64, 162-174.

[8] P. Abelha, I. Gulyurtlu, D. Boavida, J. S. Barros, I. Cabrita, J. Leahy, B. Kelleher and M. Leahy, 2003. Combustion of poultry litter in a fluidized bed combustor, Fuel, 82, 687-692.

[9] A. Demirbas, 2004. Combustion characteristics of different biomass fuels, Progress in Energy and Combustion Science; 30: 219–230. doi: 10.1016/j.pecs.2003.10.004.

[10] F. Okasha, 2007. Staged combustion of rice straw in a fluidized bed. Experimental Thermal and Fluid Science, 32, 52-59.

[11] F. Scala and P. Salatino, 2002. Modeling fluidized bed combustion of high-volatile solid fuels. Chemical Engineering Science, 57:1175–96.

[12] P. Basu, 2013. Biomass gasification, pyrolysis and torrefaction. Practical design and theory, Academic Press.

[13] Q. Yu, C. Brage, G. Chen and K. Sjöström, 1997. Temperature impact on the formation of tar from biomass pyrolysis in a free-fall reactor, Journal of Analytical and Applied Pyrolysis, 40-41, 481-489,

[14] J. Collazo, J. Porteiro, D. Patiño and E. Granada, 2012. Numerical modeling of the combustion of densified wood under fixed bed conditions. Fuel, 93, 149-159.

[15] Y. Shen and K. Yoshikawa, 2013. Recent progress in catalytic tar elimination during biomass

gasification or pyrolysis-A review, Renewable and Sustainable Energy Reviews, 21, 371-392.
[16] K. Görabsson, U. Söderlind, J. He and W. Zhang, 2011. Review of syngas production via biomass DFBGs. Renewable and Sustainable Energy Reviews, 15, 482-492.
[17] A. Gómez-Barea, B. Leckner, 2010. Modeling of biomass gasification in fluidized bed, Progress in Energy and Combustion Science, 36, 444-509.
[18] B. Leckner, 2024. From bubbling to circulating fluidized bed combustion - development and comparison, Heliyon, 10, 1-13.
[19] Z. Chen, S. Zhao, J. Zhang, X. Xu, Y. Zhang, E. Zh ou, C. Duan, 2024. Effect of fluidized bed shapes on gas-solid fluidization characters and flow regime transition, Chemical Engineering Research and Design, 204, 147-158.
[20] Y. Xie, Y. Chen, Z. Fang, H. Zhou, S. Wei, L. Yan g, 2023. The research of gas-solid fluidized bed bubbling behavior based on CFD-DEM coupled simulation, Chemical Engineering Research and Design, 195, 166-180.
[21] L. von Berg, A. Anca-Couce, C. Hochenauer, R. Scharler, 2023. Multi-scale modelling of a fluidized bed biomass gasifier of industrial size (1 MW) using a detailed particle model coupled to CFD: Proof of feasibility and advantages over simplified approaches, Energy Conversion and Management, 286, 117070.