Energy Proceedings
Vol 56, 2025
ISSN 2004-2965

Computational Fluid Dynamics Analysis of Pressure Drop in Advanced Swirling Fluidized Bed Combustion

Opeyemi Fadipe[1*], Seong Lee[1], Guangming Chen[1], Steve Efe[2], Zheng Li[3]

1 Industrial and System Engineering, Morgan State University

2 Civil Engineering, Morgan State University

3 Mechatronics Engineering, Morgan State University
(Corresponding Author: opfad1@morgan.edu)

ABSTRACT

Fluidized bed combustion (FBC) presents numerous advantages over conventional combustion technologies, making it a superior choice for various applications. The application of Computational Fluid Dynamics (CFD) is crucial in understanding and optimizing the performance of fluidized bed combustors. CFD techniques allow for the detailed simulation of complex combustion processes and the hydrodynamics within the fluidized bed, including interactions between solid particles and gas phases. The Eulerian-Eulerian model, which treats gas and solid phases as interpenetrating continua and incorporates the kinetic theory of granular flow, is particularly effective in capturing these dynamics. In this study, we investigated the co-combustion of poultry litter with natural gas in an advanced swirling fluidized bed combustor, focusing on the pressure drop associated with poultry waste combustion. Key parameters examined included the chamber's primary air flow rate, poultry litter flow rate, and sand mass. The results indicated that increased primary air mass flow rate leads to a higher pressure drop across the combustion chamber. Excessive airflow can potentially force sand out of the chamber, highlighting the need for optimal airflow regulation. Similarly, a higher sand mass within the chamber also results in a greater pressure drop, suggesting the necessity of balancing the bed material mass to maintain efficient combustion without excessive pressure drop. The study underscores the importance of understanding the interplay between primary air flow rate, fuel feed rate, and bed material mass. Proper control and optimization of these variables are crucial for maintaining stable combustion and preventing operational issues such as bed material ejection. By accurately modeling and analyzing the effects of various operational parameters using CFD, it is possible to enhance fluidized bed combustors' efficiency, stability, and safety. This research demonstrates explicitly that managing the primary air flow rate and sand mass is essential for controlling the pressure drop and ensuring the effective co-combustion of poultry litter with natural gas.

Keywords: Computational Fluid Dynamics, Poultry Litter, Advanced Swirling Fluidized bed, Eulerian-Eulerian model

NONMENCLATURE

Symbols	
α_i	Phasic volume fraction
ρ_i	Physical density of phase i
$\vec{v}_i$	Velocity of phase i
$\dot{m}_{ji}$	Characterizes the mass transfer from the i^{th} to j^{th} phase
$\dot{m}_{ij}$	Characterizes the mass transfer from phase i to phase j
S_i	Source term
h_i	Specific enthalpy of the i^{th} phase
$\vec{q}_i$	Heat flux
Q_{ji}	Intensity of heat exchange between the i^{th} to j^{th} phases
h_{ij}	Interphase enthalpy
$\bar{\bar{\tau}}_i$	The i^{th} phase stress- strain tensor

1. INTRODUCTION

The significance of combustion energy cannot be overemphasized; hence, several experiments has been undertaken to increase the efficiency of energy use, decrease pollutant emissions, and minimise the negative impacts of combustion products on heat transfer surfaces. The United States Department of Agriculture

This is a paper for the Applied Energy Symposium: MIT A+B, Aug. 12-15, 2024, Cambridge, USA.

reports that statistical data shows there is an annual production of poultry and livestock in the US, with the data indicating that 8.4 billion poultry, 100 million cattle, sheep, and goats, and 8 million and 60 million swine, respectively, are produced annually (USDA: NASS, 2021). Owing to the potentials of combustion energy, manure and litter products are valued higher than animal goods. In the United States, there are thought to be 300 million tonnes of animal waste annually, including manure and litter (Lawson and Samson, 2001).

Furthermore, using fossil fuels produces substantial amounts of air pollution emissions. These pollutants include greenhouse gas emissions (C02, CH4, etc.), which are linked to global warming, and oxides of sulphur (SOx) and nitrogen (NOx), which cause acid rain and ozone layer depletion. Federal rules addressing the discharge of air pollutants have grown particularly strict due to environmental and public health concerns. The majority of control techniques are essentially costly. Co-combustion of biomass is one of the less expensive options that have grown in favour with energy production plants. In general, wood waste products like sawdust and wood chips are included in biomass fuel. In addition, it can comprise municipal animal and industrial wastes like sewage sludge, manure, and agricultural leftovers like maize husks and wheat chaff, among others (Wang et al., 2009).

According to the Danish Energy Agency, bioenergy generated 70% of the country's renewable energy in 2017 (Parajuli, 2012). In Denmark, renewable energy accounts for nearly 40% of overall energy consumption. Biomass may be used as an energy source that is CO2-neutral through thermochemical processes including gasification and combustion (Saidur et al., 2011; Yue et al., 2014; Cherubini, 2011). While gasification generates syngas gas that may be burnt or used to manufacture chemicals or liquid fuels, combustion attempts to generate heat and energy. Fixed-bed reactors (Blasi et al., 2003), fluidized bed reactors (Nguyen et al., 2012), and entrained flow reactors (i.e., entrained flow gasifiers and pulverised combustors) are all capable of performing biomass gasification and combustion. Computational Fluid Dynamics (CFD) has been created to describe biomass combustion and gasification to aid in optimizing these processes.

Early in the 1970s, Computational Fluid Dynamics, or CFD as often known, emerged as an acronym for a set of physical, mathematical, and, to some extent, computer science techniques used to model fluid flows. Fluids are a crucial condition of matter, particularly in the process industries where they play a significant role. A material in the liquid or gas phase is referred to as fluid. The characteristics of a fluid are crucial to how it flows. When fluids are exposed to a shear or tangential force, their characteristics respond appropriately. Therefore, a fluid may deform under the effect of shear stress, regardless of how little. Stress is known to be inversely related to strain in fluids and to strain rate in solids (Angel et al., 2020).

Fluidized beds are utilised in a variety of industrial processes, including coating procedures employed in the pharmaceutical sector and fluid catalytic cracking, combustion, gasification, and pyrolysis (Huahai et al., 2020; Mohamad et al., 2020). Most significantly, the current need for more sustainable, cleaner energy has propelled biomass applications to the front of the list of potential answers. Wood chips, straw, maize stalks, animal dung, and other types of organic waste are all examples of biomass feedstock. The varieties of feedstock stated make it very evident that these don't represent normal flammable material. These materials are poor candidates for traditional combustion due to their form, water content, and frequently low heating values; fluidized bed technology can be used in their place (Cui and Grace, 2007).

2. LITERATURE REVIEW

Biomass refers to organic materials, such as wood, agricultural residues, and other biological materials, that can be used as a renewable energy source (Perea-Moreno et al., 2019). Biomass has been a major energy source for nearly 50% of the world’s population, particularly in the developing world (Riahi et al., 2011). The demand for biomass by large Industrial Plants to reduce fossil fuel costs and mitigate greenhouse gas emissions underscore its significance as a sustainable energy source (Areias et al., 2020). Biomass is a renewable energy source that can provide low-cost, emission-free solutions for generating electricity (Fraga et al.,2019; Rubin et al., 2015).

Poultry Litter is a mixture of poultry excreta, feathers, wasted feed, and bedding materials from poultry houses (Gutierrez et al., 2022). The United States is a significant producer of poultry litter, generating approximately 10.2 million tons of dry matter waste annually from poultry production (Pote et al., 2011). Careful consideration of environmental and health impacts is essential in managing the substantial volumes of poultry litter generated annually. Disposal of poultry litter is a complex issue that requires sustainable and environmentally responsible management practices. Heavy Studies have explored various thermochemical conversion processes such as fast pyrolysis, gasification, and combustion to harness the energy potential of poultry litter (Pandey et al., 2019).

3. METHODOLOGY

This FBC system had a diameter of 304.8 mm and a height of 1500 mm. The chamber was fabricated with a carbon steel pipe, covered inside with a 12.7 mm thickness refractory ceramic to reduce heat loss. The Primary Air (PA) for combustion was supplied at the bottom of the chamber at varying speeds. Above this line, the feed (poultry litter) was introduced from a screw feeder at a varying rate and the secondary air lines were introduced tangentially to the bed at heights of 650 mm, 850 mm, and 1100 mm. The natural gas (NG) was fed at heights of 120 and 150 mm above the air distributor plate. (Alamu et al., 2023) The Schematic Chart of the fluidized bed combustion is presented above.

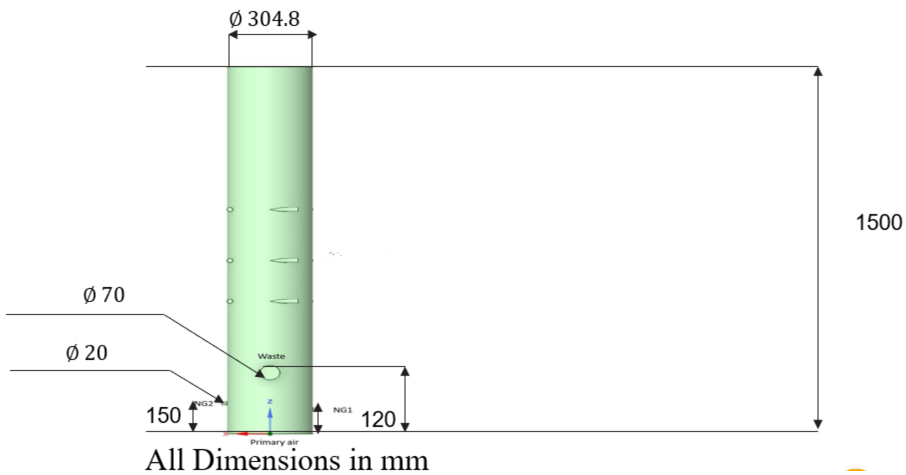

Fig. 1 Fluidized Bed Combustion

The computational fluid dynamics (CFD) analysis was carried out using the Eulerian-Eulerian model in ANSYS Fluent 2021 R2 to simulate gas-solid interactions in fluidized bed combustion systems. This model treats gas and solid phases as interpenetrating continua, solving momentum, energy, and continuity equations for each phase simultaneously. The kinetic theory of granular flow (KTGF) was incorporated to capture particle collisions, energy dissipation, and frictional interactions, critical for micro-scale dynamics in swirling fluidized beds. The reactor geometry was developed in ANSYS Design Modeler, and a high-resolution computational mesh was generated to ensure accuracy in critical regions, balancing efficiency and precision. Boundary conditions were set to replicate swirling gas flow, with no-slip wall interactions and the waste for this analysis was the poultry litter. The proximate and ultimate analyses of the poultry litter are from Zhu and Lee (2005). Pressure drop and swirling intensity were analyzed to understand their effects on hydrodynamic stability and particle mixing under varying the primary air mass flow rate, poultry litter mass Flow rate, and sand mass.

Mass Conservation

$$\frac{\partial}{\partial t}(\alpha_i\rho_i) + \nabla.(\alpha_i\rho_i\vec{v}_i) = \sum_{j=1}^{n}(\dot{m}_{ji} - \dot{m}_{ij}) + S_i \quad \textbf{(3.1)}$$

Momentum Conservation

$$\frac{\partial}{\partial t}(\alpha_i\rho_i\vec{v}_i) + \nabla.(\alpha_i\rho_i\vec{v}_i\vec{v}_i) = -\alpha_i\nabla \mathbf{p} + \nabla.\bar{\bar{\tau}}_i + \alpha_i\rho_i\vec{g} + \sum_{j=1}^{n}(\vec{R}_{ji} + \dot{m}_{ji}\vec{v}_{ji} - \dot{m}_{ij}\vec{v}_{ij}) + (\vec{F}_i + \vec{F}_{lift,i} + \vec{F}_{vm,i}) \quad \textbf{(3.2)}$$

$$\bar{\bar{\tau}}_i = \alpha_i\mu_i(\nabla\vec{v}_i + \vec{v}_i^T) + \alpha_i\left(\lambda_i - \frac{2}{3}\mu_i\right)\nabla.\vec{v}_i\bar{\bar{I}} \quad (3.3)$$

Energy Conservation

$$\frac{\partial}{\partial t}(\alpha_i\rho_i h_i) + \nabla.(\alpha_i\rho_i\vec{v}_i h_i) = \alpha_i\frac{\partial P_i}{\partial t} + \bar{\bar{\tau}}_i + \nabla\vec{v}_i - \nabla.\vec{q}_i + S_i + \sum_{j=1}^{n}(Q_{ji} + \dot{m}_{ji}h_{ji} - \dot{m}_{ij}h_{ij}) \tag{3.4}$$

4. RESULTS

Figure 2 illustrates that as the primary air flow rate increases from 0.14 kg/s to 0.165 kg/s, the pressure drop rises steadily, indicating greater resistance caused by enhanced fluidization. A notable sharp increase in pressure drop after 0.155 kg/s suggests a transition to a fully fluidized or more turbulent regime, requiring higher energy input for air supply. This analysis, derived from CFD, is essential for optimizing the balance between efficient fluidization and energy consumption in advanced combustion systems.

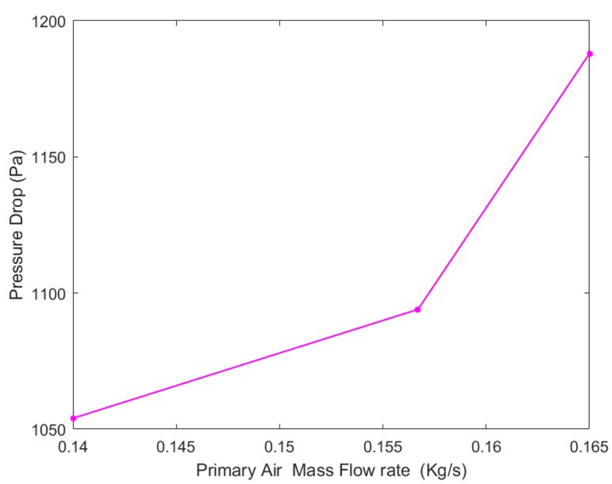

Fig. 2 Pressure Drop Against the Primary Air Mass Flow rate

Figure 3 shows that the poultry litter mass flow rate increases from approximately 1×10^{-3} to 2×10^{-3} kg/s, the pressure drop rises sharply, peaking at around 1100 Pa. Beyond this peak, as the mass flow rate further increases to 3×10^{-3} kg/s, the pressure drops declines significantly to around 940 Pa. This trend suggests an optimal mass flow rate for maximum pressure drop, likely linked to the fluidization dynamics and particle-air interactions, after which excess mass flow may reduce effective fluidization or cause system instability. In Figure 4, As the sand mass increases from 6 kg to 8 kg, the pressure drop consistently rises from approximately 1000 Pa to around 1120 Pa. This positive correlation indicates that higher sand mass introduces greater resistance to airflow, leading to an increased pressure drop. The trend highlights the role of bed material (sand) in influencing the fluidization dynamics, as greater sand mass likely increases the particle density and frictional interactions within the system.

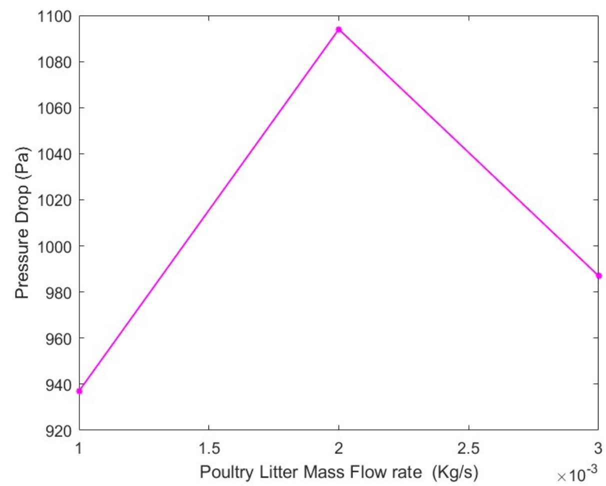

Fig. 3 Pressure Drop Against the Poultry Litter Mass Flow rate

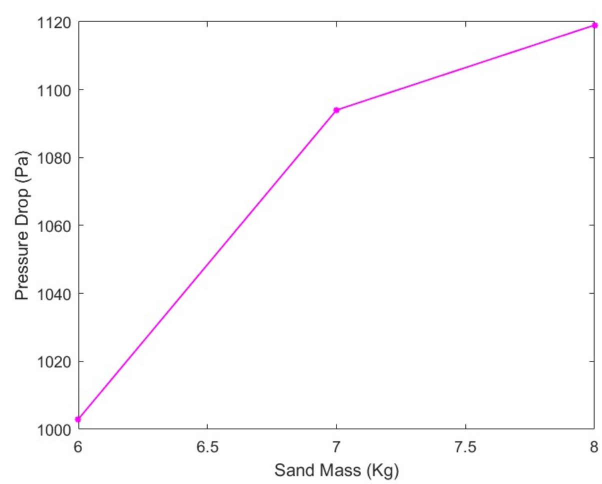

Fig. 4 Pressure Drop Against Sand Mass

5. CONCLUSION

The pressure drop is affected by the sand mass and primary air mass flow rate, there is no much significant effect by the poultry litter flow rate. The pressure drop is directly related to the fluidization quality of the bed material. The pressure drop in fluidized bed combustion is a key parameter that affects the efficiency, stability, and operational cost of the system. Proper monitoring and control of pressure drop are essential for achieving optimal performance in FBC systems.

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