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Analysis and Design for a Horizontal Gasifier: Review Paper

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Abstract

The increasing demand for sustainable energy solutions has driven more research into alternative energy sources, including biomass-derived methane. This review paper discusses the analysis and design considerations of horizontal gasifiers in the context of efficient methane production and waste management. It covers the technical, environmental, and economic aspects of gasification technologies, underlining the role of fluidized bed systems and CFD modeling in optimizing combustion processes. Advanced gas collection systems, innovative design configurations, and catalytic enhancements have been discussed as being important for improving methane yield and reducing emissions. The paper also discusses various new trends in hydrothermal gasification and direct methanation, with much emphasis on the need for interdisciplinary approaches to overcome existing biomass conversion technology challenges. It indicates the vital contribution that horizontal gasifiers make in the production of renewable energy and to global sustainability.

Keyword: *Horizontal Gasifier; Biomass Gasification; Renewable Energy; Computational Fluid Dynamics (CFD); Methane Production*

1. Introduction:

The increase in prices of fossil fuel and the alarming environmental effects of global warming and exhaust fumes have been the main driving forces for researchers to find alternative sources of energy. One of the promising areas is the collection of methane from landfills, which has attracted much attention in developed nations.
Biomass is a biological organic matter produced by photosynthesis: plants, animals, microorganisms, and waste from those organisms. As a renewable carbon source, biomass boasts low-price advantages, abundant reserves, and little pollution. Production from biomass will lower the emission of greenhouse gases to a great extent [1].

Methane is a natural resource that results from the anaerobic fermentation of organic waste by bacteria in a digester. It is also the main constituent of natural gas. When collected from landfills, methane can be used for different purposes, including electricity generation, heating buildings, or as fuel for waste collection vehicles. This process provides a renewable energy source and a means of decreasing methane emissions into the atmosphere, thereby reducing its overall contribution to climate change.

The design of the collection systems of methane is an important factor to consider for the effectiveness of this approach. Advanced technologies for gas collection can enormously increase the efficiency of the capture, thus minimizing emissions and enhancing the potential production of energy. As indicated in Figure 1., integrating such systems successfully illustrates a very important step toward overcoming energy and environmental issues.

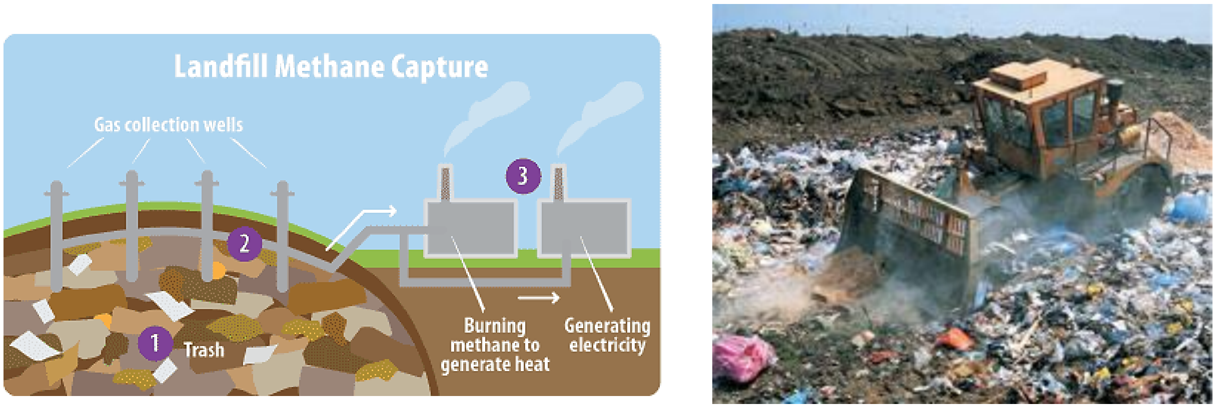


Figure 1. Landfill Methane Capture [2]

2. Technical ways to reuse waste

The global urban population is growing more rapidly-1.5%-compared to the growth rate of the total population. Most of the population resides in urban areas, which has resulted in global increases in municipal solid waste (MSW) generation, mostly due to population growth, urbanization, and economic development. Presently, the MSW generation rate in developed countries is more than that of developing countries because the generation rate depends on a country's economic and social prosperity [3]. People in developing nations are slowly getting accustomed to the way of life in developed countries due to globalization. Due to this, enormous amounts of waste are produced within developing nations. Therefore, changes in food habits, consumption patterns, and living standards of the urban population are mainly responsible for the rise in the MSW generation rate [4].

Table 1: Summary of Key Research Contributions on Waste Management and Energy Recovery Technologies

Author(s)	Focus/Key Area	Summary of Contributions
Tan et al., 2014 [5]	Recycling vs. Energy Recovery	Highlighted recycling as a preferred waste management method and its positive

		correlation with energy recovery rates in developed nations.
Achillas et al. [6]	Waste Management Practices in Developing Countries	Identified landfilling as the dominant method in developing countries and its association with low recycling rates.
Kumar & Samadder [3]	MSW Treatment Technologies	Discussed the aims of waste management, optimal technology selection, and detailed the products of thermal, biological, and landfill processes.
Kalyani & Pandey, [7]	Waste Conversion Technologies	Reviewed thermal, biological, and landfill methods for waste processing, including incineration, pyrolysis, and anaerobic digestion.
Appels et al. [8]	Feasibility of Thermal Conversion Technologies	Highlighted challenges in adopting pyrolysis and gasification at scale due to poor feedstock quality and MSW characterization.
Brunner & Rechberger, [9]	Evolution of Incineration Technology	Discussed the transition from incineration for volume reduction to its current role in energy recovery, supported by pollution control advances.
Psomopoulos et al. [10]	Incineration in Developed Countries	Noted the dominance of incineration in developed regions due to high regulatory standards and its suitability for urban areas.
Scarlat et al. [11]	Incineration Regulations	Reported stringent waste disposal regulations driving incineration's prevalence in EU, US, and Japan.
Lombardi et al. [12]	Pyrolysis for Waste Conversion	Highlighted the process and product diversity of pyrolysis, with emphasis on recycling specific waste streams like scrap tires.
Yap & Nixon, [13]	Gasification as a WTE Technology	Explored gasification's environmental benefits and

		potential for syngas production, although large-scale adoption remains limited.
Luz et al. [14]	Limitations of Pyrolysis and Gasification	Identified barriers to scaling WTE technologies, such as poor gas cleaning systems and MSW heterogeneity.
Wang & Geng, [15]	Environmental Impact of Landfilling	Emphasized the environmental consequences of landfilling in developing nations and stressed minimizing its use to 10–15% of total waste.
Kumar & Chakrabarti, [16]	Waste Disposal in Developing Countries	Described landfilling practices in developing nations and their associated environmental degradation.
Müller et al. [17]	Pollution from Landfill Leachate	Discussed the hazards of landfill leachate and its impact on groundwater and surface water bodies.
Yang et al. [18]	Fluidized Bed Technology	Reviewed the history and application of fluidized beds in energy production from solid fuels.
Yliniemi , [19]	Fluidized Bed Boilers	Illustrated the operation and heat transfer processes in fluidized bed boilers.
Demirbas, [20]	Biomass as Renewable Energy	Presented biomass as a sustainable energy source, with thermochemical conversion methods like pyrolysis, gasification, and liquefaction.
Pucker et al. [21]	Gasification of Forest Residues	Conducted a life-cycle assessment showing the environmental benefits of gasification over natural gas combustion.
Wu et al. [22]	Methane as a Gaseous Fuel	Highlighted the advantages of methane for energy distribution, including cost-efficiency and compatibility with existing infrastructure.

Arafat et al. [23] reported the average recoverable energy contents in terms of electrical energy efficiency for different components of MSW utilizing different Waste to Energy (WTE) technologies. Figure 2 illustrates that anaerobic digestion was the best-suited WTE option for food and yard wastes whereas gasification was the best WTE option in treating plastic wastes.

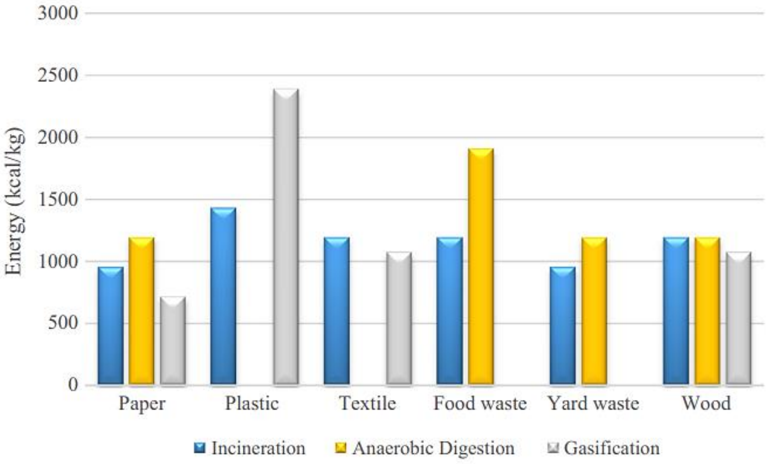


Figure 2 Energy recovery potential of different WTE technologies for different MSW streams [3]

The aims of any waste management system are material and energy recovery, followed by disposal of the residues. However, an optimal choice for waste processing technology is not only subject to economic requirements, energy recovery, or waste destruction ability but also to look for environmental regulatory compliance requirements of the concerned area. Therefore, the best available technology for waste processing that fulfills all the required criteria for a successful operation must be chosen. There are several kinds of processes for waste conversion in the three most applied technologies are [7]: (i) thermal conversion [(incineration, pyrolysis, gasification, production of energy from refuse derived fuel (RDF)], (ii) biological conversion (anaerobic digestion/biomethanation and composting), and (iii) landfilling with gas recovery. The MSW treatment techniques along with the typical reaction products are shown in Figure 3, [3].

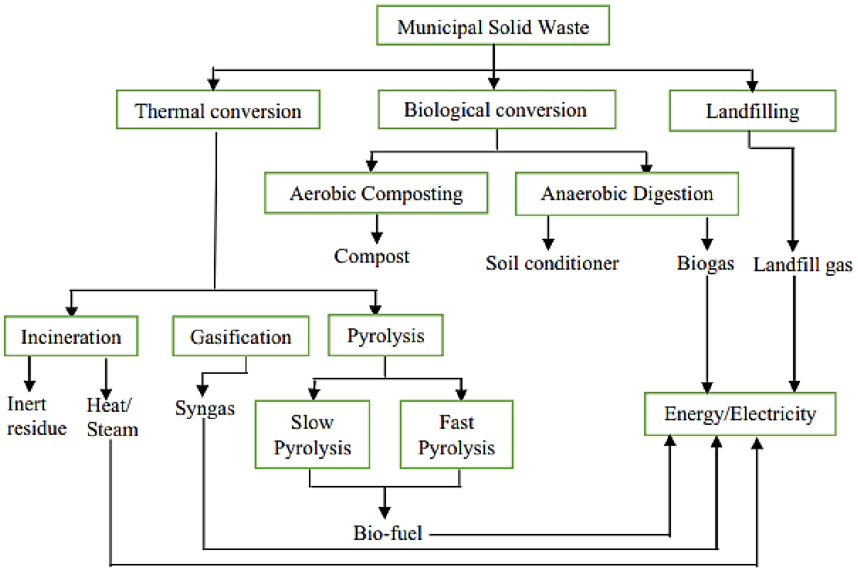


Figure 3 Municipal solid waste treatment techniques and their products. [3]

Gasification is another thermal conversion technology whereby organic compounds are converted into syngas in a controlled atmosphere of oxygen at high temperatures. Syngas, the major product of the gasification process, may be used for energy generation through combustion. It may also be used to produce feedstock for chemicals and liquid fuel [13]. Most of the reported studies of gasification are related to the homogeneous flow of solid fuels like coal, wood, etc., and specific kinds of MSW. The technology of gasification was highly used in the coal industry, but lately, it has been considered one of the promising options for energy recovery from MSW[23].

Pyrolysis and gasification technologies can reduce waste volumes by 95% and require less intensive flue gas cleaning compared to incineration. Pyrolysis and gasification techniques are superior to other WTE options due to environmental emissions and efficiency in energy recovery. However, they remain to be established on a large scale around the world - especially in developing countries - for energy recovery from MSW [14]. This is due to the poor efficiency of gasifiers and gas cleaning systems, heterogeneity in MSW composition and particle size, and high moisture content.

The term sanitary landfilling refers to the disposal of wastes on land with minimization of the impact in a controlled manner using leachate management and recovery of biogas. Figure 4, Whereas in unsanitary conditions of landfilling, relatively simple and inexpensive practices have generally been adopted as the common option of waste disposal in many developing countries, due to an increase in quantity over the years [15]. Previous studies showed that landfilling causes the highest environmental impact compared to other waste management options. It has been reported that in most of the cities of developing countries, the waste is disposed of in low-lying areas located on the outskirts of the city [16]. Landfilling has become the worst option, taking into consideration the associated environmental impact, health impact, land degradation, and groundwater contamination. However, through stringent regulations on waste reduction and recycling, developed countries have started discouraging landfilling of waste. The landfill leachate is one of the major polluting substances that is released from landfills or dumpsites. This is a dark effluent, which has an unusually variable composition and is reported to have recalcitrant compounds. Müller et al. [17] which pollutes the nearby surface watercourses and groundwater aquifers. As experts say, only 10–15% of the total waste generated should go to landfilling and it should be the last option for cities where land is limited.

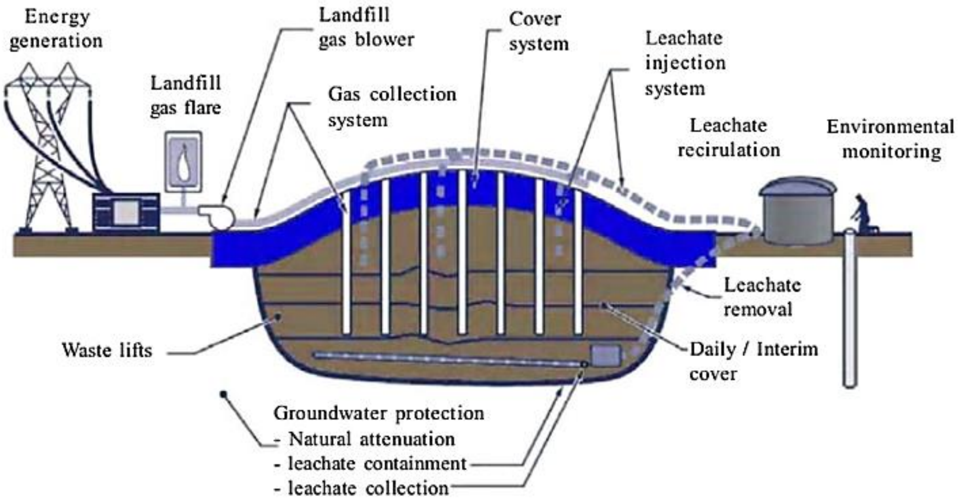


Figure 4 . A typical engineered landfill with a biogas recovery system. [3]

In industrial production, several methods can be used to mix solid and gas streams, which include fixed beds, moving beds, entrained flow beds, and fluidized beds. For the design of the gas-solid system, adequate contact between the two phases of solids and gas must be ensured. To solve the energy crisis, since the 17th century FB technology has been developed. During the last few decades, hydrodynamic, chemical, and physical processes in fluidized beds have been the subject of extensive investigation. The solid fuels in FB furnaces undergo thermo-conversion with a high temperature of inert material, ash, and limestone-which is fluidized by upward fluid flow as shown in Figure 5. The inert material in the furnace does not participate in chemical reactions but provides heat transfer to fuels [18].

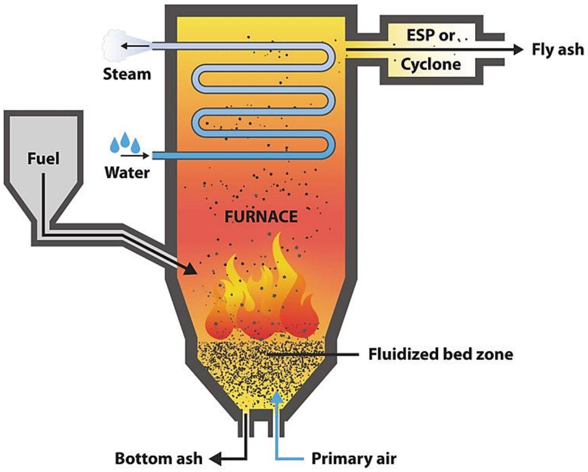


Figure 5. Schematic Illustration of fluidized bed boiler [19]

The quest for energy from sustainable sources has taken center stage in recent years, compelled by the imperative need to reduce climate change and dependence on fossil fuel supplies. Biomass is a promising renewable energy source produced from organic materials like agricultural residues, forestry by-products, and dedicated energy crops [20]. Besides, Biomass can be utilized as a solid fuel or transformed into liquid and gaseous forms to generate electric power, heat, chemicals, or gaseous and liquid fuels. Thermochemical conversion processes are classified into three sub-classes: pyrolysis, gasification, and liquefaction. Biomass thermal conversion processes can be illustrated in Figure 6. Its use is not only for energy security, but it also reduces waste and results in carbon neutrality. The combustion of biomass releases energy in the form of heat, which makes it ideal for many applications: to produce electricity and heat and for industrial processes. Combustion of biomass also produces some unique challenges. First, the variability in biomass composition can lead to inconsistent combustion performance and potentially variable emissions. Besides, there are several disadvantages with conventional combustion systems: incomplete combustion often occurs, accompanied by high particulate emissions and the formation of NOx and VOC pollutants. Therefore, optimization in biomass combustion processes is extremely important to ensure high efficiency with minimal environmental impact.

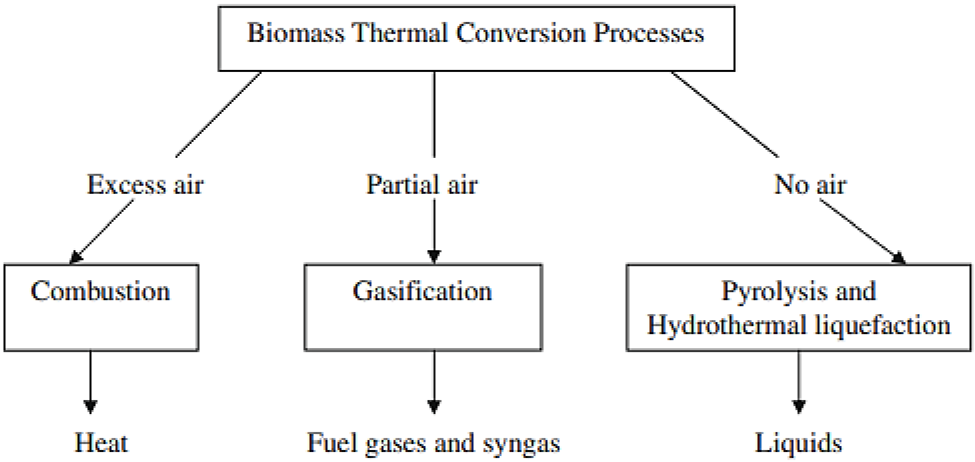
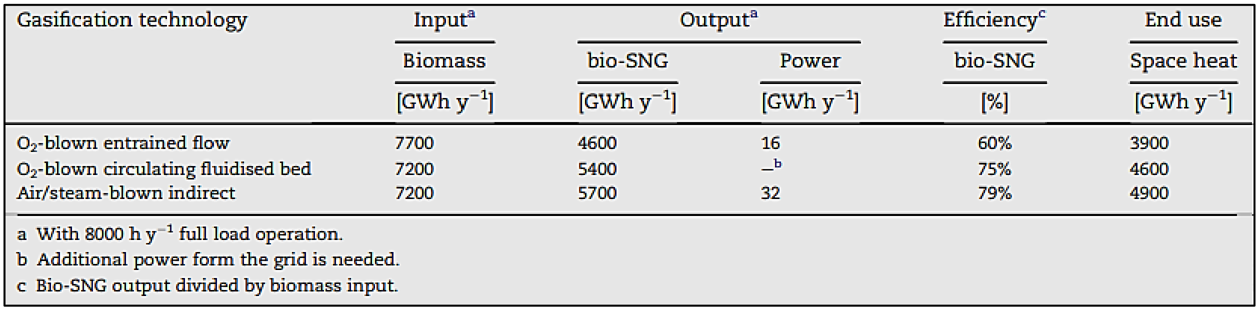


Figure 6. Biomass thermal conversion processes. [20]

According to a life cycle assessment by Pucker et al. [21] Greenhouse gas emissions from the forest residues via air-steam indirect gasification technology are 80% lower in comparison with natural gas, and 29% from burning wood chips. Basic data for these gasification technologies can be seen in Table 1. Compared to hydrogen, the other gaseous fuel from biomass, methane does not migrate through the metal lattice of most materials in the gas transportation pipeline. It therefore can reutilize existing natural gas infrastructure and substitute natural gas. Transportation and distribution cost of methane is cheaper than that of hydrogen [22]. Moreover, high energy efficiency could also be obtained from the conversion of biomass to methane.

Table 1 Characteristics of (substitute natural gas) bio-SNG systems [21]



Gasification technology	Input[a]	Output[a]		Efficiency[c]	End use
	Biomass	bio-SNG	Power	bio-SNG	Space heat
	[GWh y^{-1}]	[GWh y^{-1}]	[GWh y^{-1}]	[%]	[GWh y^{-1}]
O_2-blown entrained flow	7700	4600	16	60%	3900
O_2-blown circulating fluidised bed	7200	5400	–[b]	75%	4600
Air/steam-blown indirect	7200	5700	32	79%	4900

a With 8000 h y^{-1} full load operation.
b Additional power form the grid is needed.
c Bio-SNG output divided by biomass input.

3. CFD Simulation Techniques

In the past few years, remarkable progress has been attained in improving the accuracy and stability of numerical methods and algorithms. Computational fluid dynamics (CFD) has been applied as an important design tool in various industrial zones, and the CFD techniques have shown the capability to provide an accurate prediction for some chemical processes [24].

CFD gives a numerical approximation to the equations of motion that describe the fluid flow. The application of CFD to analyze a fluid problem involves the following: First, the mathematical equations that describe the fluid flow are written. These are usually a set of partial differential equations. These equations are then discretized to produce a numerical analog of the equations. The domain is then divided into small grids or elements. Finally, these equations are solved with the help of the initial and boundary conditions of the specific problem. All CFD codes possess three main elements: (1) A pre-processor, which is used to input the problem geometry, generate the grid, and define the flow parameter and the boundary conditions to the code. (2) A flow solver, which solves the governing equations of the flow subject to the conditions provided. There are four different methods used as a flow solver: (i) finite difference method; (ii) finite element method, (iii) finite volume method. (3) A post-processor, which is used to massage the data and show the results in a graphical and easy-to-read format [25].

4. Mathematical formulation

In the present model, the governing equations of the continuous and discrete phases involved in fluidized bed furnaces are described in the Eulerian and Lagrangian frameworks, respectively. The governing equations of the continuous and discrete phases and main sub-models involved in the 3-D model are described in the present study. In the context of horizontal biomass burners, CFD modeling allows researchers and engineers to investigate various design configurations and operational parameters. This can visualize flow patterns and thermal behavior within the burner to find the optimal conditions that lead to efficient combustion. Additionally, CFD will help in predicting the emission profile for different operating scenarios and thus help in planning strategies to minimize environmental impacts as shown in Figure 7.

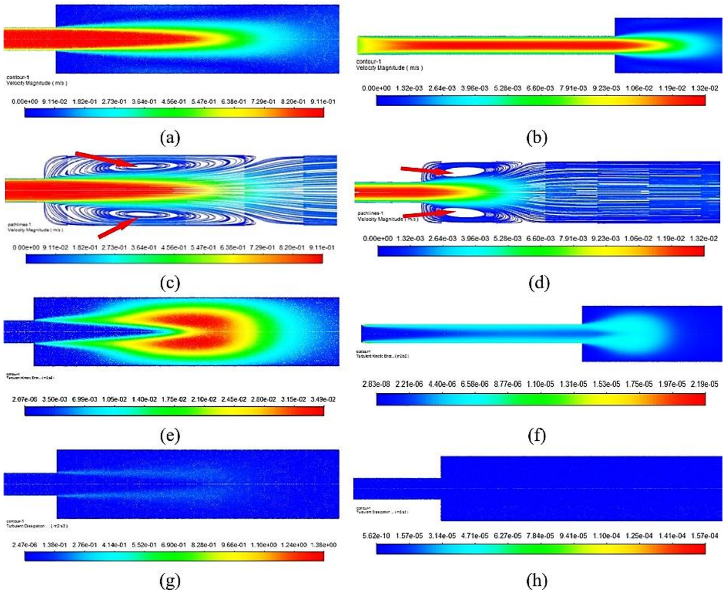


Figure 7. Flow patterns and thermal behavior within the burner using CFD Software [26]

The prime route of methane production by the thermochemical conversion of biomass is via gasification. Instead of the gasification route, which includes the reaction stage, this paper will focus on the stage of gas conditioning and methanation-a stage playing a key role in the increase of methane concentration [22]. This review covers the description of the methanation reaction, the catalysts, and the reasons for and methods of gas conditioning; it summarizes environmental and economic assessments. Finally, hydrothermal gasification, fast pyrolysis, and low-temperature direct methanation will also briefly be exposed [27]. Considering such factors, an attempt is made to discuss in detail the future research directions to arrive at an improved production of methane by thermochemical conversion of biomass.

Recent studies have illustrated the capabilities of CFD for modeling biomass combustion processes. For example, the study conducted CFD simulations to analyze a horizontal cyclonic combustion chamber that was specially designed for pulverized biomass fuels. Their results illustrated how CFD could be used to assess combustion performance and thus provided an opportunity for burner design optimization to improve efficiency and reduce emissions.
In addition, flue gas particulates in biomass stoves were studied using CFD models to optimize the technologies for their removal; this further extends the application of CFD in biomass energy systems [28], shown in **Figure 8**.

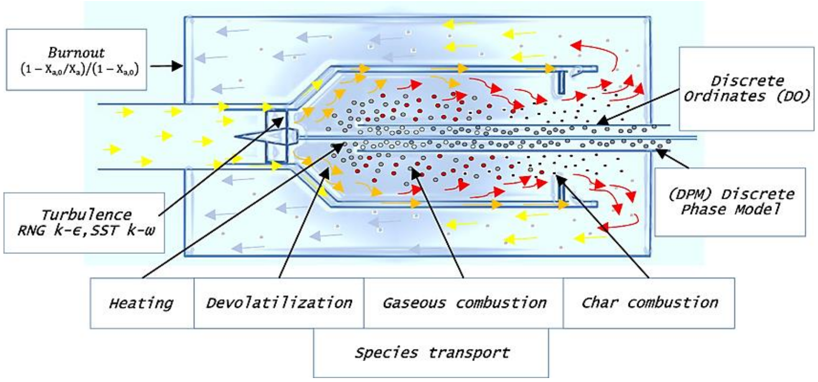


Figure 8. FLUENT models used in the combustion chamber simulations [28]

Silva et al. [29] presented a critical review of biomass thermal analysis, focusing on the combustion kinetics and product distribution. Their work underlines the key parameters that control biomass thermal decomposition, which is vital in developing the best conditions in combustion chambers represented in Figure 9. The study outlines the importance of understanding the thermal characteristics of biomass toward the improvement of combustion modeling and efficiency.

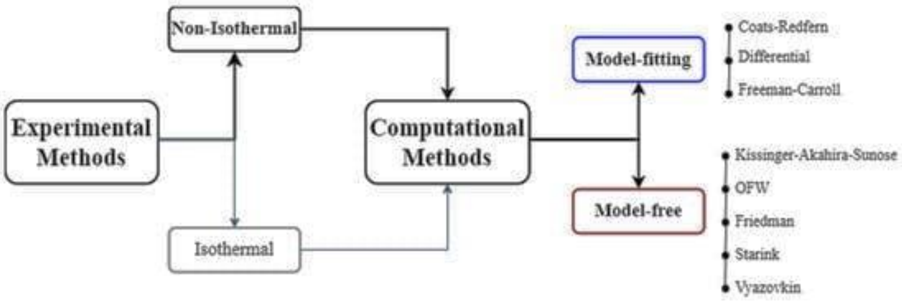


Figure 9 An overview of the methods for solid-state kinetics studies [20]

According to a report by IEA Bioenergy in 2023, while biomass combustion can effectively substitute for fossil fuels and mitigate CO2 emissions, it also presents challenges regarding harmful emissions, such as particulate matter (PM) and volatile organic compounds (VOCs). Combustion technologies have evolved, with more efficient and cleaner combustion. The report mentions that this calls for the deployment of modern systems, which would be able to answer air quality concerns [30].

García Sánchez et al. [31] reviewed the state-of-the-art CFD modeling of biomass boilers, underlining the different numerical methods used for the optimization of combustion processes. They mentioned that though CFD offers great advantages due to the improvement in design and operational conditions, several limitations still exist in the complexity of thermochemical reactions and the large use of computational resources.

Research by Dula et al. [32] measured combustion efficiency for several types of solid biofuels, such as pellets and briquettes made from plant biomass. It was observed from their experiments that automatic fuel feeding caused the stabilization of the combustion process; thus, efficiency was enhanced, and emissions were reduced compared with traditional methods.

Kumar et al. [33] performed a CFD of a horizontal biomass gasification reactor using ANSYS CFX solver, where gasification air velocity, species mass fractions of biomass, turbulence eddy dissipation, and Eddy viscosity have been studied. Moreover, Liu et al. [34] used a CFD model with an Eulerian multiphase approach to simulate fluidization in biomass gasification using air as the gasifying agent. For the momentum exchange, different viscous models were considered, with a greater emphasis on the RNG k-epsilon model. The RNG model gave the best agreement with experimental pressure drop data. Turbulence modeling, chemical reaction modeling, multi-phase flow simulation, validation techniques, and optimization methods have been some of the advanced modeling approaches that have been tried to understand coal combustion and gasification processes better and make them more efficient [35].

Von Berg et al. [36] performed a coupled multi-scale simulation of more than 30 seconds of process time using 300,000 inert bed parcels and approximately 25,000 reacting fuel parcels. The model was able to do this with feasible calculation times, showing efficiency in handling the complex interactions within the reactor. Eisavi et al. [37] estimated the overall exergy efficiency of the system to be 36.8% under base conditions. The levelized costs of electricity, methanol, and methane are calculated to be 37.6, 92.8, and 79.4 $/MWh, respectively. Yang et al.

[38] have emphasized the NOx emission processes. NOx emissions remain one of the most important because of the contribution they make to air pollution, smog, and acid rain. The analysis of NOx formation in the furnace helps in developing strategies to minimize these emissions during biomass combustion.

5. Conclusion

The review underscores the significant role of Computational Fluid Dynamics (CFD) in enhancing the efficiency and sustainability of horizontal gasifiers for biomass-to-methane conversion. As global energy demands rise alongside environmental concerns, optimizing gasification technologies becomes increasingly critical. CFD modeling provides insights that lead to improved design parameters, enhanced combustion efficiency, and reduced emissions. It allows for the simulation of various gasifier designs under different operational conditions, helping identify optimal configurations that maximize methane yield while minimizing byproducts. Additionally, CFD aids in understanding pollutant formation mechanisms during gasification, enabling adjustments to reduce harmful emissions and align with sustainability goals. Recent advancements in catalytic methanation and waste conditioning further improve methane production efficiency, working synergistically with CFD-optimized gasifiers. Future research should focus on scaling up technologies from pilot to commercial scales, enhancing preprocessing techniques for biomass feedstocks, and exploring hybrid systems integration to achieve efficient energy recovery. Overall, the integration of CFD into the development of horizontal gasifiers represents a significant advancement in biomass-to-methane conversion technologies, contributing to broader environmental sustainability as society moves towards renewable energy solutions.

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