Chapter 2: State of the Art of the Gasification-CI engine

This chapter includes an overview of the gasification process and its components, including a summary of the different properties of feedstocks for gasification as well as the different components of the producer gas filtration process in terms of their characteristics and their variants. Furthermore, the details of different gasifiers and variable compression ratio technology with its advantages are also discussed. Optimisation of different operating variables are also discussed for the best output responses. Furthermore, the state of art of economic analysis of waste-to-fuel conversion through briquetting and gasification-engine power system are also discussed in the following section.

2.1 Gasification

Gasification is a thermochemical process that converts carbonaceous materials, such as coal, biomass, or waste, into a gaseous fuel known as producer gas through incomplete combustion. This producer gas typically consists of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), small amounts of methane (CH_4), and a substantial amount of nitrogen (N_2). The gasification process takes place at elevated temperatures in the presence of a controlled amount of oxygen or steam, but not enough to fully combust the feedstock. Instead, it partially oxidizes the material, breaking it down into its gaseous components.

The gasification process typically involves the following key steps:

Feedstock Preparation: The carbonaceous material, which can be in various forms like coal, wood chips, or municipal solid waste, is prepared and often pretreated to remove impurities like moisture and contaminants.

Gasifier: The prepared feedstock is introduced into a gasifier, a high-temperature vessel or reactor. Depending on the type of gasification technology used, oxygen and/or steam are also introduced into the gasifier.

Chemical Reactions: Inside the gasifier, the feedstock undergoes chemical reactions, which can be represented by the following simplified equations:

a) **Partial Oxidation:** $C + O_2 \rightarrow CO$

b) **Steam Reforming:** $C + H_2O \rightarrow CO + H_2$

These reactions result in the formation of carbon monoxide (CO) and hydrogen (H_2) primarily, along with other gases depending on the feedstock and gasification conditions.

Gas Cleanup: The raw syngas produced in the gasifier may contain impurities like tars, particulates, sulfur compounds, and nitrogen oxides. Gas cleanup processes are employed to remove these impurities and ensure the syngas meets specific quality standards.

Producer gas Utilization: The clean syngas can be used for various purposes, including:

- Power generation in gas turbines or internal combustion engines.
- Production of chemicals, such as methanol or ammonia.
- Fuel for heating or industrial processes.
- As a feedstock for the production of synthetic fuels or chemicals.

Gasification offers several advantages, including the ability to use a wide range of feedstocks, high energy efficiency, and reduced greenhouse gas emissions compared to traditional combustion processes. It also enables the production of valuable chemicals and fuels from low-cost feedstocks. Thus, Gasification technology has applications in power generation, waste-to-energy conversion, and the production of clean fuels and chemicals, making it an important area of research and development for addressing energy and environmental challenges.

Furthermore, the gasification feedstock is extremely flexible, as almost all organic fuels like coal, biomass, and solid wastes can be gasified as shown in Figure 2.1.1.

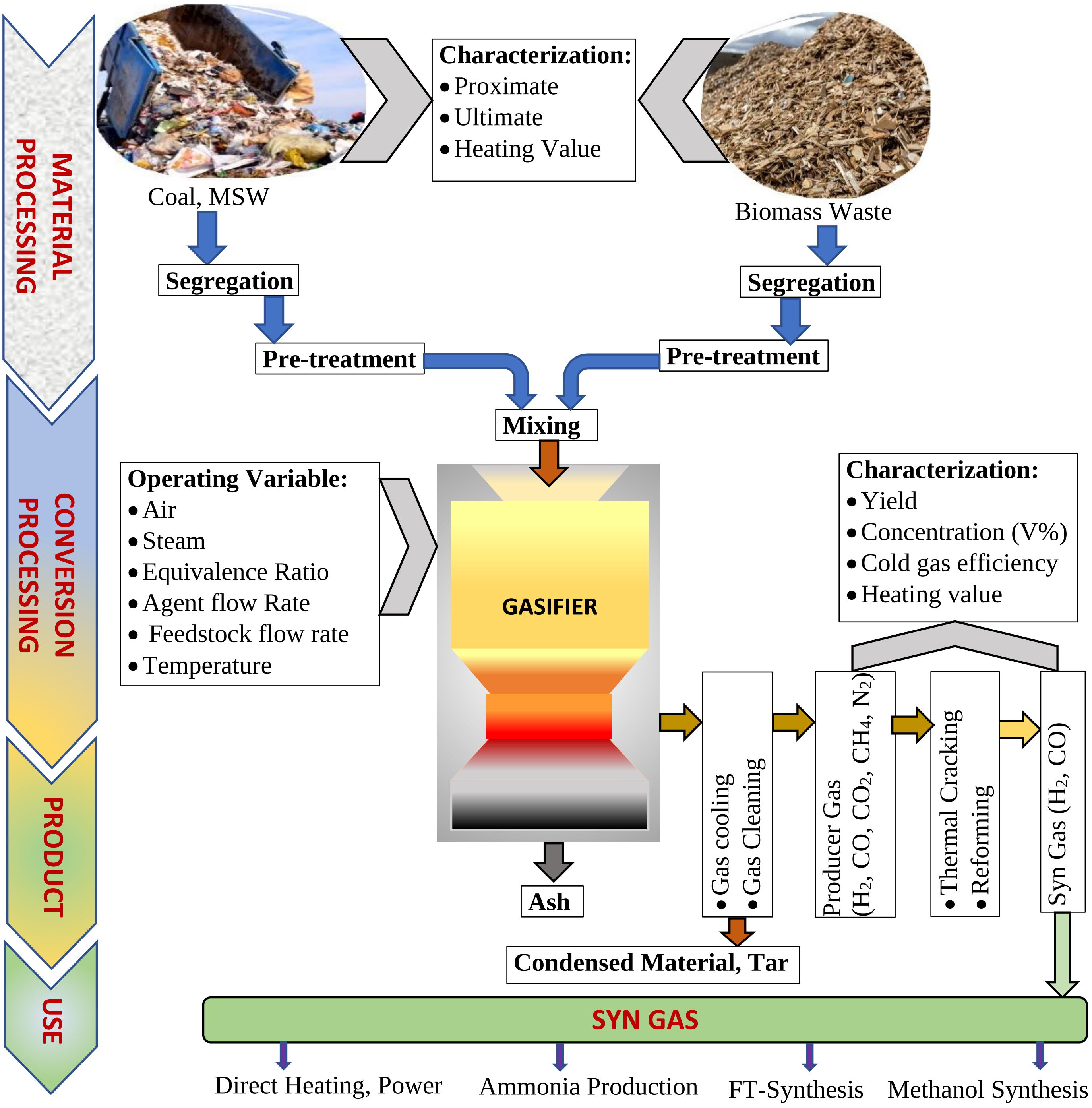


Figure 2.1.1. Schematic of gasification to product application

Gasification occurs in different phases involving a variety of chemical processes. However, it may be summarized as four main stages: drying wet feedstock, Pyrolysis, oxidation and reduction reactions containing reforming and cracking reactions in the gaseous state, and the gasification of heterogeneous char [116] [117]. Figure 2.1.2 summarizes these steps.

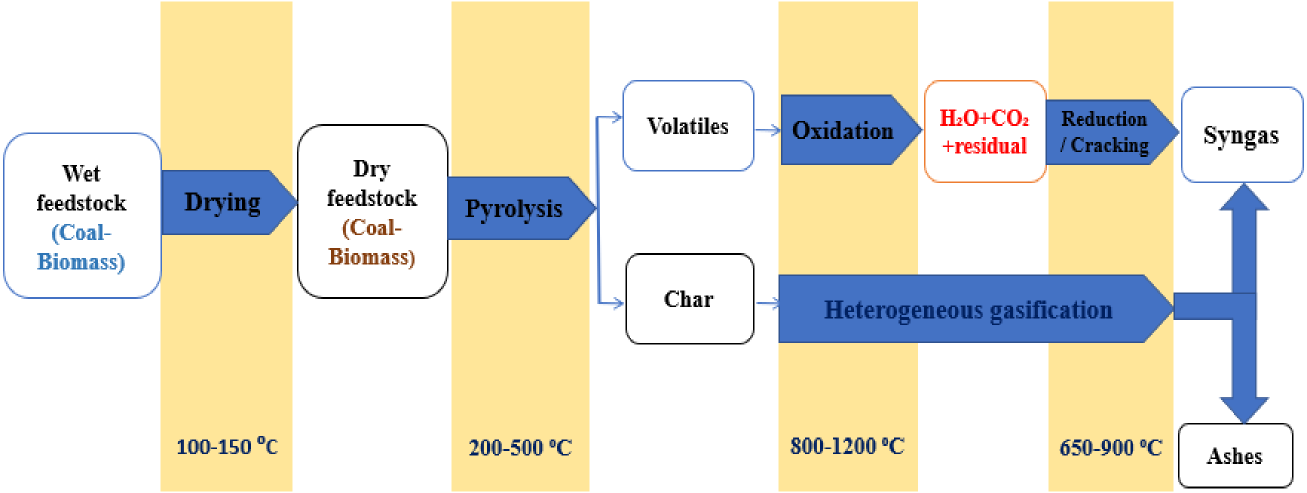


Figure 2.1.2. Schematic of the principal steps in co-gasification of coal-biomass wastes

2.2 Chemistry of gasification

2.2.1 Drying Zone

In this initial zone, the feedstock is heated, and moisture content is removed through evaporation. The temperature in this zone is relatively low, typically below 200°C. Drying is an essential step because moisture in the feedstock can consume energy and reduce the efficiency of the gasification process. Only the phase transition between the liquid water and the steam water [118] occurs, and there is no chemical reaction at this step. Since the moisture has external humidity, its drying process is generally fast and is not undergo any diffusional restrictions [117].

2.2.2 Pyrolysis Zone

The pyrolysis process entails a sequence of complex endothermic reactions that result in volatile gases and some solid char residuals. Because of feedstock's physical and chemical properties, pyrolysis is a crucial zone in their gasification. Beyond the drying zone, as the temperature continues to rise (usually between 200°C to 600°C, the feedstock undergoes pyrolysis. During pyrolysis, the solid carbonaceous material is thermally decomposed into volatile gases, tar, and char. The main reactions in this zone are the thermal decomposition reactions:

- Solid → Gases (volatile compounds) + Tar + Char

The volatile gases produced in this zone will further react in the subsequent zones to form syngas.

2.2.3 Oxidation Zone

In the presence of an oxidant and at high temperatures, heterogeneous and homogeneous reactions take place between the source material and the oxidant, leading to the production of CO and water steam. This occurs under sub-stoichiometric oxygen conditions. The oxidation process is influenced by multiple factors, including the type of oxidant employed, chemical composition of the feed, and the operating conditions. The exothermic nature of this stage predominates, and the thermal energy released during the reactions serves as the essential heat source for the overall process [116].

Oxidation Reaction:

$C + O_2 \rightarrow CO_2 \qquad \Delta H = -393.5\ kJmol^{-1} \qquad (2.1.1)$

$H_2 + \frac{1}{2} O_2 \rightarrow H_2O \qquad \Delta H = -285.9\ kJmol^{-1} \qquad (2.1.2)$

2.2.4 Reduction Zone

It's an endothermic step that occurs in the lack of O_2 at elevated temperatures [116]. Steam facilitates two reactions: the endothermic steam reforming of tar and, char and the exothermic water-gas shift reaction. These reactions result in the generation of H_2 [119]. The production of H_2 is the result of both approaches. The most efficient technique to increase H_2 production is to reduce the amount of water used in steam gasification [120]. CO is produced when CO_2 combines with char. It's known as the boudouard reaction, a type of endothermic reaction [121]. During oxy-fuel combustion/gasification, CO_2 can be re-circulated along with oxygen [122].

Reduction Reaction:

Boudouard:

$$C + CO_2 \leftrightarrow 2CO \qquad \Delta H = 172.50 \text{ kJ/mol} \qquad (2.1.3)$$

Char steam reforming:

$$C + H_2O \rightarrow H_2 + CO \qquad \Delta H = 131.30 \text{ kJ/mol} \qquad (2.1.4)$$

Water gas shift reaction:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H = -41.20 \text{ kJ/mol} \qquad (2.1.5)$$

Carbon hydrogenation reaction:

$$C + 2H_2 \rightarrow CH_4 \qquad \Delta H = -74.9 \text{ kJ/mol} \qquad (2.1.6)$$

Methane reforming:

$$CH_4 + H_2O \leftrightarrow 3H_2 + CO \qquad \Delta H = 205.8 \text{ kJ/mol} \qquad (2.1.7)$$

Steam gasification of hydrocarbon:

$$C_nH_m + 2nH_2O \rightarrow \left(2n + \frac{m}{2}\right) H_2 + nCO_2 \qquad (2.1.8)$$

2.3 Biomass feedstock for gasification

The choice of biomass feedstock depends on factors such as regional availability, energy density, moisture content, and the specific requirements of the gasification technology being used. It's essential to select feedstocks that are sustainable and do not compete with food production or lead to deforestation, which can have adverse environmental impacts.

Additionally, pre-processing steps such as drying, grinding, and sorting may be required to prepare the biomass feedstock for efficient gasification. Proper feedstock preparation and handling are crucial for the success of gasification processes. Proximate and ultimate analyses are essential methods for characterizing the composition and properties of gasification feedstock, providing valuable information for the design and operation of gasification processes. Table 2.3.1 shows the proximate and ultimate analysis of different feedstocks for the gasification.

Table 2.3.1. Proximate and Ultimate analysis of different feedstocks

Ultimate analysis (wt. %)						**Proximate analysis (wt. %)**				
Biomass	**C**	**H**	**N**	**O**	**S**	**VM**	**FC**	**Ash**	**Moisture**	**Ref.**
Corn straw	43.83	5.95	0.97	45.01	0.13	75.95	13.75	5.93	6.17	[123]
Dalbergia sisoo	48.6	6.2	0.33	44.87	NG	80.40	15.70	3.90	-	[124]
Hazzlenut shell	45.9	5.7	<1	48.2	0.072	68.2	18.2	1.1	12.4	[125]
Corn stalk	47.54	6.02	0.77	43.87	0.13	69.5	12.2	5.8	12.5	[126]
Poultry litter	43.98	5.16	4.63	31.98	0.75	63.6	15.3	13.5	7.6	[28]
Eucalyptus	46.78	5.92	0.324	45.55	0.09	83.01	15.66	1.34	12.23	[127]
Oil palm fronds	44.58	4.53	0.71	48.80	0.07	83.5	15.2	1.3	16	[128]
Acacia wood	50.22	5.90	0.25	43.01	0.02	65.12	21.12	3.91	9.56	[129]
Peanut shell	44.34	6.35	0.79	45.47	0.29	65.65	17.34	5.96	11.41	[130]
Jatropha seed husk	48.5	5.7	0.67	41.8	0.01	71.04	24.99	3.97	10.75	[131]
Black pine pellet	49.58	6.65	0.19	43.59	-	83.58	15.83	0.61	4.64	[132]

Ultimate analysis (wt. %)							**Proximate analysis (wt. %)**			
Biomass	**C**	**H**	**N**	**O**	**S**	**VM**	**FC**	**Ash**	**Moisture**	**Ref.**
Peach	48.06	5.83	0.55	44.03	-	84.80	13.90	1.53	9.8	[133]
Olive	46.43	5.63	0.55	44.91	-	72.7	16.2	2.48	10.6	[133]
Pine	48.18	5.71	0.15	43.89	-	84.5	15.1	2.07	9.0	[133]
Miscanthus pellet	41.51	4.85	0.4	35.08	0.04	63.9	18	6.5	11.58	[134]
Rice husk pellet	46.6	6.2	0.7	37.4	0.1	65.1	16.4	9.3	9.2	[37]
Larch sawdust	48.5	6.4	0.1	44.7	0.3	76.7	19.9	0.8	2.6	[37]

Proximate and ultimate analyses are essential for several reasons:

- It provides information about the combustion and gasification behaviour of the feedstock.
- It helps in calculating the higher heating value (HHV) or lower heating value (LHV) of the feedstock, which is crucial for energy conversion processes.
- It assists in understanding the potential for emissions and environmental impacts.

The results of these analyses guide the selection of appropriate gasification technologies, the design of gasification systems, and the development of operating parameters to optimize the conversion of biomass into syngas or other products. Additionally, the data can be used to assess the environmental sustainability and emissions profile of the gasification process.

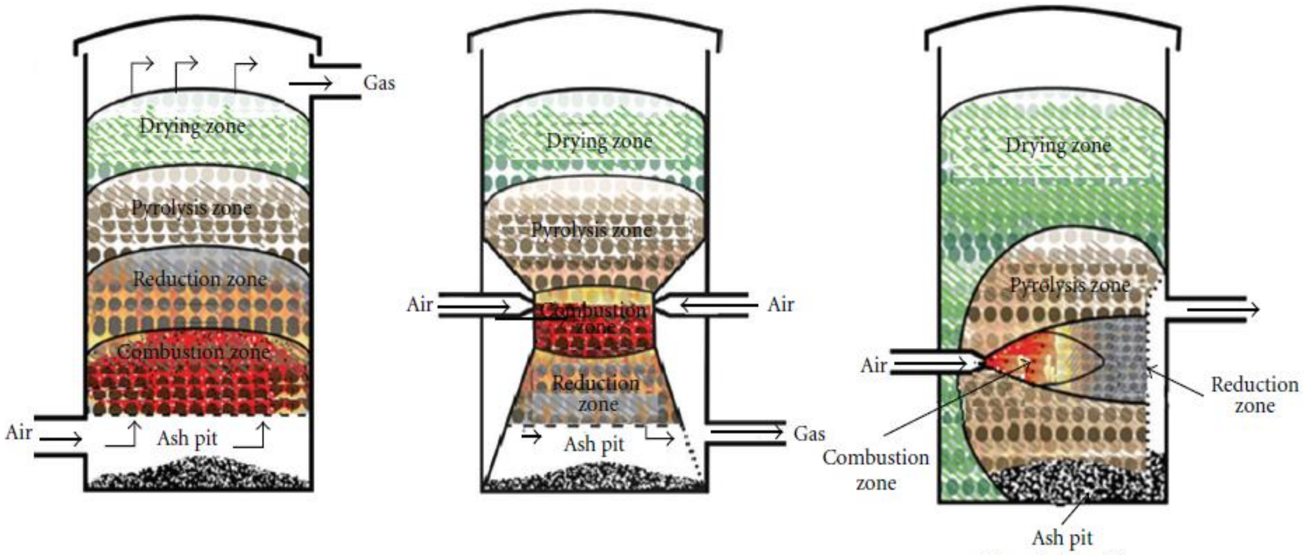
Gasifiers are devices used in biomass gasification and other thermochemical processes to convert various feedstocks into syngas (synthetic gas), which is a mixture of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), and other trace gases. There are several types of gasifiers, each with its own operating principles, advantages, and disadvantages. Here are some common types of gasifiers:

1. **Fixed Bed Gasifier:** Fixed bed gasifiers operate on a batch or semi-continuous basis. The feedstock is loaded into a fixed bed, and the gasification process takes place within the bed. Fixed bed gasifiers are relatively simple but may have limitations in terms of feedstock size and quality control. The fixed bed type gasifier is further categorized into a downdraft, updraft, and cross draft gasifier according to the interaction of fuel and air, and these are discussed in this present study.

    a) **Updraft Gasifier:** In an updraft gasifier, the feedstock is loaded at the top, and the gasification process progresses downward through the bed of biomass. Air or oxygen is introduced at the bottom, and the syngas is drawn off from the top. Updraft gasifiers are relatively simple and have a lower tar content in the syngas, making them suitable for small-scale applications.

    b) **Downdraft Gasifier:** Downdraft gasifiers are designed so that air or oxygen is introduced at the top, and the gasification process occurs as the feedstock moves downward through the reaction zone. Downdraft gasifiers typically produce cleaner syngas with lower tar content than updraft gasifiers. They are commonly used in applications such as small-scale power generation and heating.

    c) **Crossdraft Gasifier:** A crossdraft gasifier, also known as a cross-draught gasifier, is a type of gasification reactor used to convert solid feedstocks such as biomass or coal into syngas (synthetic gas). The term "crossdraft" refers to the direction of air or gas flow across the bed of the feedstock, perpendicular to the feedstock's movement. In a crossdraft gasifier, the feedstock is typically introduced horizontally into the gasifier chamber. Crossdraft gasifiers are known for their simplicity and ease of operation compared to other gasifier types. They are often used in small-scale or pilot-scale gasification applications for decentralized energy generation, heating, and biochar production. Figure 2.3.1 shows the flow line diagram of updraft, downdraft, and crossdraft gasifier.



(a) Updraft gasifier (b) Downdraft gasifier (c) Crossdraft gasifier

Figure 2.3.1 Flow line diagram of Updraft, Downdraft, and Crossdraft gasifier [135].

2. **Fluidized Bed Gasifier:** Fluidized bed gasifiers suspend the feedstock in a fluidized bed of inert material, such as sand or ash, using an upward flow of gas (usually air or steam). This creates a highly efficient and uniform environment for gasification. Fluidized bed gasifiers are known for their flexibility in handling various feedstocks and their ability to control the gasification process. They are used in applications ranging from power generation to chemical production.

3. **Entrained Flow Gasifier:** Entrained flow gasifiers operate at high temperatures and pressures and are often used in industrial-scale applications. In this type of gasifier, finely ground feedstock is entrained in a high-velocity stream of gas (usually oxygen

or a mixture of oxygen and steam). This results in rapid and efficient gasification. Entrained flow gasifiers are known for their high syngas quality and are used in industries such as steel production and chemical manufacturing.

4. **Two-Stage Gasifier:** Some gasification systems use a two-stage approach, where the first stage is a partial oxidation or pyrolysis reactor, followed by a second-stage gasification reactor. This approach can enhance syngas quality and reduce tar content.
5. **Bubbling Fluidized Bed Gasifier:** This is a variation of the fluidized bed gasifier where the bed of inert material behaves like a bubbling fluid. Bubbling fluidized bed gasifiers are often used for biomass gasification and offer good control over the gasification process.

The choice of gasifier type depends on factors such as the feedstock, desired syngas quality, scale of operation, and specific application requirements. Each type of gasifier has its advantages and disadvantages, and the selection should be based on the intended use and project goals. The advantages and disadvantages of different types of gasifiers are depicted in Table 2.3.2.

Table 2.3.2. Advantages and disadvantages of different types of gasifiers.

Reactor Type	Advantages	Disadvantages
Fixed bed “Updraft”	- High thermal efficiency. - Good contact between the solid material and the oxidizing agent. - Can handle materials of different sizes. - Can handle materials with high humidity. - Reduced entrainment both of dust and that of Ashes. - Simple construction.	- High content of tar in the syngas. - Energy content of tar > 20%. - Low production of CO and H_2. – requires a subsequent treatment of the tar cracking. - Limited flexibility to load and process. - Reduced starting difficulties and temperature control.

		- According to catalysts, they may be not usable since syngas energy may be lower than that necessary for the activation, requiring external energy supply - Poisoning deactivation of catalysts may be possible.
Fixed bed “Downdraft”	- Robust technology - There are no problems of scale-up. - High carbon conversion. - Limited entrainment of ash and dust. - High sold residence time. - Simple construction. - Reliable technology.	- Low specific capacity. - Need for uniform sizes in input. - Limited flexibility to load and process. - Low coefficient of heat transfer. - Difficulty starting and controlling the temperature. - Limited possibility of scale up.
Entrained flow reactor	- Fuel flexibility. - Uniform temperature. - High carbon conversion. - No problems of scale-up. - Good ability to control the parameters process. - Short reactor residence time. - Very low tar concentration. - High temperature slagging operation.	- Large oxidant requirements. - High level of sensible heat in product gas. - Heat recovery is required to improve efficiency. - Low cold gas efficiency. - Requires the reduction of size and preparation supply. - High plant cost. - High maintenance cost.
Bubbling fluidized bed	- High mixing and gas-solid contact. - High carbon conversion. - High thermal loads. - Good temperature control. - Can handle materials with different characteristics. - Good flexibility both of load and process.	- Loss of carbon in the ashes. - Dragging of dust and ashes. - Pretreatment need with heterogeneous materials. - Restrictions on the size. - High investment costs and maintenance costs.
Circulating fluidized bed	- Lower tar production. - High conversions. - Flexible load. - Reduced residence times. - Good ability to scale-up.	- Possibility of casting the ashes. - Loss of carbon in the ashes. - Restricted solid-gas contact. - Need for special materials. - Security issues. - High start-up costs and investment costs.

2.4 Post-gas treatment

Gas treatment is an essential step in the gasification process to ensure that the syngas produced meets the required quality standards and is suitable for various applications, such as power generation, chemical synthesis, or fuel production. Post-gas treatment involves several operations to clean and condition the syngas before it is used or further processed. The water-based scrubber, cyclone separator, and filtration are the post-gas treatment system after gasification, and these units play specific roles in the purification and cooling of the producer gas (PG) in a gasification system. Figure 3.2.1 shows the post gas treatment of gasification units. Followings are the details of how they contribute to removing contaminants and ensuring the quality of the producer gas:

- **Water-Based Scrubber:**

Function: The water-based scrubber is responsible for removing particulate matter, tar, and certain gaseous contaminants from the PG.

Operation: The PG enters the scrubber, where it comes into contact with a water spray or mist. The water droplets capture the solid particles, tar, and some soluble contaminants through impingement, condensation, and absorption processes.

Contaminant Removal: The water-based scrubber effectively removes fine particles, ash, and tar, which may be present in the PG stream. It helps in preventing the downstream equipment from fouling and reduces the potential for environmental pollution.

- **Cyclone Separator:**

Function: The cyclone separator primarily removes larger particulate matter and solid particles from the PG stream.

Operation: The PG enters the cyclone separator tangentially, creating a vortex motion. The centrifugal force causes the solid particles to move toward the outer walls of the cyclone, where they settle and are collected in a hopper at the bottom.

Contaminant Removal: The cyclone separator is effective in removing relatively larger particles, such as ash and coarse particulate matter. By separating these particles, it helps prevent their accumulation in downstream components and ensures the quality of the PG.

- **Filtration Unit:**

Function: The filtration unit further removes remaining fine particulate matter and contaminants that may have passed through the scrubber and cyclone separator.

Operation: The PG was allowed to pass through three chamber filtration units (Rice husk, wood dust, and heavy cotton cloth) in a sinusoidal trajectory, which trap and retain small particles and contaminants.

Contaminant Removal: The filtration unit enhances the purification process by capturing finer particles that were not captured by the scrubber or cyclone separator. It improves the overall quality of the PG, making it suitable for downstream applications or emission control devices.

Overall, these components work together in a gasification system to ensure the quality of the producer gas by removing various contaminants, including particulate matter, tar, ash, and soluble impurities. Their combined action helps protect downstream equipment, maintain system efficiency, and meet emission regulations or quality requirements for the engine application and storage of the producer gas.

2.5 Power generation through IC engine

The producer gas from biomass gasification can be used as a fuel for engine applications. The choice of an IC engine for biomass gasification depends on factors such as the scale of the application, efficiency requirements, emissions regulations, and economic considerations. Some of the common types of IC engines used in conjunction with biomass gasification, along with their advantages and disadvantages:

- **Gasoline Engines:**
    - *Advantages:*
        - Higher power density compared to other internal combustion engines.
        - Smoother operation and lower noise levels.
    - *Disadvantages:*
        - Higher operating temperatures, which can lead to increased wear and maintenance requirements.
        - Typically, gasoline engines are not as fuel-efficient as diesel engines.
- **Diesel Engines:**
    - *Advantages:*
        - Generally, more fuel-efficient than gasoline engines.
        - Higher torque at lower rpm, making them suitable for heavy-duty applications.
        - Longer lifespan and lower maintenance costs compared to gasoline engines.

- *Disadvantages:*
    - Higher initial costs.
    - Diesel engines may produce more NOx emissions compared to other engines.

- **Dual-Fuel Engines:**
    - *Advantages:*
        - Combining biomass syngas with diesel or natural gas can improve overall efficiency and reduce emissions.
        - Flexibility to operate on multiple fuels.
    - *Disadvantages:*
        - Complex control systems are required to manage dual-fuel combustion effectively.
        - Initial costs and complexity can be higher than single-fuel engines.

In the current experimental work, Variable Compression Ratio (VCR) engine is used as a coupling with gasifier unit due to its potential advantage. VCR engine is a type of internal combustion engine that allows for the adjustment of the compression ratio (CR), which is the ratio of the volume of the combustion chamber when the piston is at its lowest point (bottom dead center) to the volume when it's at its highest point (top dead center). The CR is a critical parameter in engine design, as it affects efficiency, power output, and emissions. VCR engines provide the ability to vary this ratio dynamically, optimizing it for different operating conditions. Figure 2.5.1 shows the VCR engine with a procedure to change CR. Here are some key aspects of VCR engines:

- **Efficiency Improvement:** One of the primary goals of VCR technology is to improve engine efficiency. By adjusting the compression ratio, VCR engines can operate at higher compression ratios under certain conditions (e.g., low-load, high-speed) to maximize thermal efficiency and fuel economy. Conversely, they can reduce the compression ratio under other conditions to prevent knocking and improve performance.
- **Reduced Emissions:** VCR engines can help reduce emissions, particularly in gasoline engines. Higher compression ratios can improve the combustion process, leading to lower emissions of greenhouse gases (such as CO_2) and pollutants (such as NOx and unburned hydrocarbons).
- **Knock Mitigation:** Knocking or detonation is a phenomenon in internal combustion engines where the air-fuel mixture detonates prematurely, leading to engine damage and reduced efficiency. VCR engines can lower the compression ratio when knocking is likely to occur, mitigating this problem.
- **Improved Performance:** VCR technology allows for optimal compression ratios for different engine loads and speeds. This means that the engine can deliver better performance when needed, such as during acceleration, without sacrificing efficiency during cruising or light-load conditions.
- **Flexibility with Fuels:** VCR engines can be adapted to run on a variety of fuels, including gasoline, diesel, natural gas, and hydrogen. The ability to adjust the compression ratio makes them versatile in different fuel applications.
- **Challenges:** Developing VCR engines presents engineering challenges, including the design of variable compression mechanisms, control systems, and durability considerations for moving parts. Ensuring reliable and cost-effective manufacturing is also crucial.

- **Hybridization:** VCR technology can complement hybrid powertrains, where it works in conjunction with electric motors to improve overall vehicle efficiency.
- **Applications:** VCR technology has been explored in various applications, including passenger cars, trucks, and industrial engines, with the potential to enhance efficiency and reduce emissions across these sectors. It's important to note that while VCR engines hold promise for improving the efficiency and emissions performance of internal combustion engines, they were still under development and testing. The adoption of VCR technology in commercial vehicles would depend on factors like cost-effectiveness, reliability, and the ongoing evolution of emissions regulations.

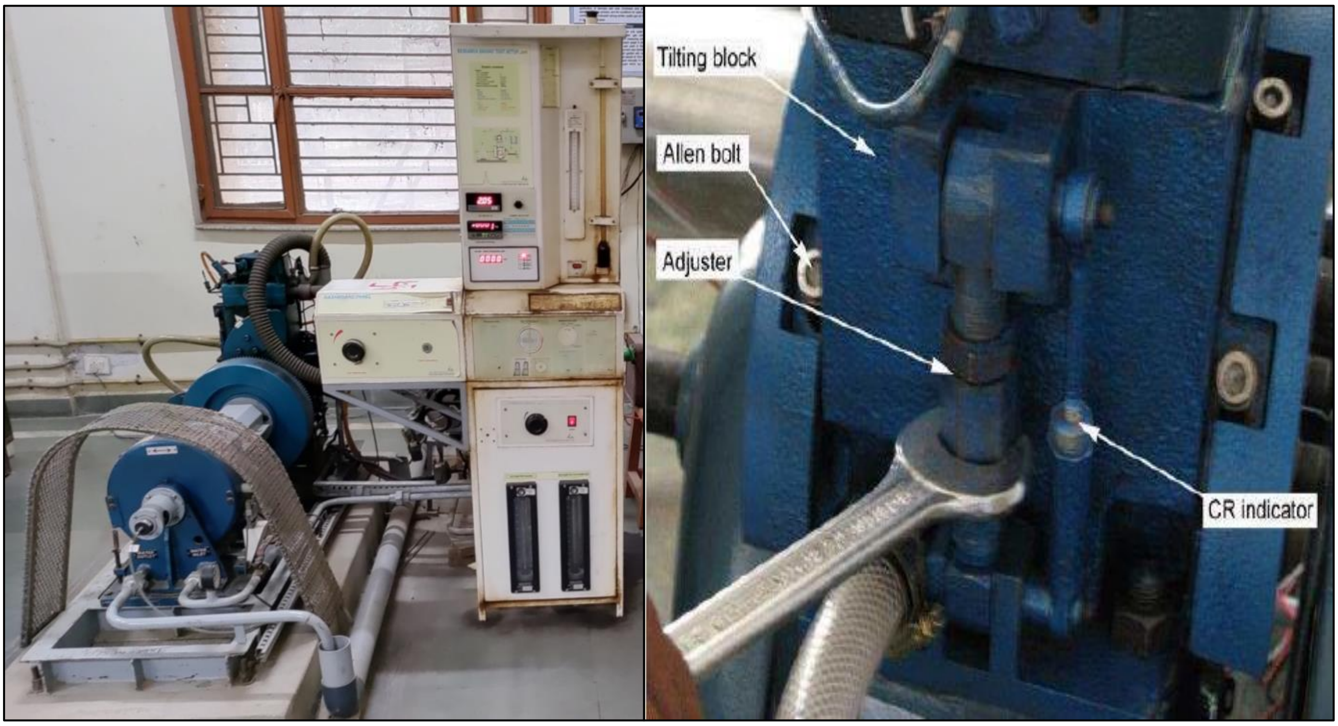


Figure 2.5.1. VCR engine with a procedure to change CR.

2.6 Optimization of gasifier-engine operating variable

The optimization of gasification-engine operating variables was an active area of research and development in the field of energy production and renewable energy. There is various methodology for optimization namely RSM, Taguchi, artificial neural network (ANN) etc. In contrast to the RSM technique, Taguchi method requires a smaller number of experiments than RSM to determine an accurate optimum condition. However, the true optimal value in the Taguchi method is difficult to determine because the true optimal factorial levels could differ from the predetermined factorial levels [136, 137]. RSM incorporates a series of mathematical/statistical procedures for making an empirical model and exploitation such that the response approaches a desired minimum or maximum value. Recently, RSM-based optimization has become very significant, due to its effectiveness to mitigate the cumulative understanding and to reduce time-consuming experimental work on performance and emission parameters [107]. Several authors had suggested the RSM optimization technique is better than conventional test methods, because, traditional methods involve varying the values of one factor and its effect on the response while holding other factors at a fixed level. Conventional test methods require many experiments and it does not study the interactions among parameters, which may influence the process. These limitations can be easily overcome by RSM techniques [137]. Moreover, RSM is based on the surface placement approach to understanding the ridgelines, the local minimum, and the maximum of the response surface, and finding the best region. One of the primary advantages of RSM is that a large amount of information can be obtained in less time and with fewer experiment trials[103]. Also, building models and graphical illustrations can be studied concerning the effects of variables and their interaction with the response. RSM typically involves fitting mathematical models to the experimental data. These models can be linear, quadratic, or more complex, depending on the nature of the relationship between factors and responses. Advanced techniques such as neural networks and machine learning models were also being explored to improve the accuracy of response surface models. However, it has some disadvantages such as, it does not explain the reason for interaction, and it is poor to predict potential results beyond the given range of operating parameters [137],[138]. The optimization of gasification-engine operating variables involves adjusting various parameters to maximize efficiency, minimize emissions, and ensure stable and reliable operation. These variables can include:

- Feedstock Type and Characteristics: The type of feedstock (e.g., wood chips, agricultural residues, coal) and its properties (e.g., moisture content, particle size) play a crucial role in gasification. Optimizing the selection and preparation of feedstock can improve gasification performance.
- Gasifier Design: The design of the gasifier itself, such as the type (fixed-bed, fluidized bed, entrained flow), size, and configuration, affects gasification efficiency and syngas quality. Researchers work on optimizing these design parameters.
- Operating Temperature: Gasification temperature is a critical variable as it influences the reaction kinetics and the composition of the syngas. The temperature needs to be controlled to ensure complete gasification of feedstock and minimize the production of undesirable byproducts like tar.
- Gasification Agent: The choice of gasification agent (air, oxygen, steam, or a combination) and its flow rate can significantly impact gasifier performance and syngas quality.
- Gasification Equivalence ratio: Optimum gasification equivalence ratio is an important parameter for enriched producer gas emission. It depends on the air flow rate to the nozzle. The calorific value of syngas significantly depends on GER.
- Gas Cleaning and Conditioning: Gas cleaning and conditioning systems are essential to remove impurities, such as tar, particulates, and sulfur compounds, from the syngas

before it is used in engines. Optimization of these systems is critical for engine performance and durability.

- Engine Operation: Parameters like engine load, air-fuel ratio, compression ratio, Brake power and operating temperature also need to be optimized for efficient and reliable power generation.
- Economic considerations: Beyond just process optimization, researchers were also considering environmental and economic factors. This includes minimizing greenhouse gas emissions and evaluating the economic feasibility of optimized operating conditions.

Research and development in the optimization field continue to evolve, driven by the need for cleaner and more efficient energy conversion technologies. Researchers and engineers are exploring advanced control systems, real-time monitoring, and data analytics to improve gasification performance.

2.7 Economic analysis of biomass briquette plant

The economic analysis of waste biomass briquettes for fuel production was an area of active research and practical application, driven by the increasing demand for sustainable and renewable energy sources. Here are some key aspects of the state of the art in the economic analysis of waste biomass briquette production for fuel:

- **Feedstock Selection**: The economic viability of biomass briquette production heavily depends on the type and availability of feedstock. Researchers were focusing on identifying suitable waste biomass sources, such as agricultural residues (e.g., rice husks, sugarcane bagasse), forestry residues, and municipal solid waste.
- **Cost Analysis**: Economic analyses typically involve assessing the capital costs (e.g., equipment, labor, infrastructure) and operational costs (e.g., feedstock procurement,

energy consumption, maintenance) associated with biomass briquette production. This cost analysis helps determine the overall economic feasibility.

- **Energy and Emission Savings**: Economic analyses often consider the environmental benefits of using biomass briquettes, such as reduced greenhouse gas emissions compared to fossil fuels. These benefits can be monetized and factored into the economic evaluation.
- **Sustainability and Life Cycle Analysis**: Economic analyses were increasingly incorporating sustainability and life cycle assessments to account for the broader environmental and social impacts of biomass briquette production. This helps provide a more comprehensive view of the economic benefits.
- **Integration with Other Technologies**: Integration with complementary technologies, such as IC engine or combined heat and power (CHP) systems, was explored to enhance the economic viability of biomass briquette use.

2.8 Economic analysis of gasification-engine system

Some of the key aspects of state of the art in the economic analysis of gasifier-integrated CI engine systems are follows-

- **Life cycle cost analysis:** Comprehensive life cycle cost analysis is commonly used to assess the economic feasibility of these systems. This analysis considers the initial capital costs, operating and maintenance costs over the lifetime of the system.
- **Fuel Flexibility:** Modern gasifier systems are designed to handle a variety of feedstocks, including wood chips, agricultural residues, and waste materials, briquettes. The economic analysis takes into account the availability of feedstocks.
- **Economic Modeling:** Economic models are used to evaluate the financial viability of gasifier-integrated CI engine systems. These models often include factors like fuel

costs, electricity and auxiliary prices, maintenance expenses, and government incentives.

- **Government Policies and Incentives:** The economic analysis is influenced by government policies, including subsidies, tax incentives, and renewable energy targets. Changes in these policies can greatly affect the financial feasibility of such systems.
- **Market Conditions:** Local energy prices and market conditions can influence the economic performance of gasifier-integrated CI engine systems. Variability in energy prices and demand is a significant factor in the economic analysis.