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Process Technology

Syngas production from air gasification of waste feedstock with natural catalyst, Olivine, as the bed material



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Summary: Gasification of biomass is a process that converts organic material into a synthetic gas (syngas) by exposing it to high temperatures in an environment with limited oxygen. This technology supports green energy goals by utilizing renewable biomass, reducing greenhouse gas emissions, and providing an alternative to fossil fuels. Coffee waste, rich in organic material and oils, offers significant energy potential, making them an effective feedstock for biofuel production. This work discusses results on pelletization, sieving of bed materials, cold bed experiment, syngas composition.

In this work, the pellets produced by the pelleting machine were used as feedstock in the gasifier to produce syngas. The waste pellets consist of a mixture of coffee grounds and sawdust. The quality and strength of the pellets decreased with higher moisture contents. The particle size distribution of the bed materials was analyzed through sieving of the bed materials. Experiments were conducted on a cold fluidized bed to determine the minimum fluidization velocity. Gasification experiments were performed in a 20 kW bubbling fluidized bed (BFB) gasifier with sand and olivine as bed materials and air as the gasifying agent. Syngas composition was assessed by gas chromatography. Various equivalence ratios (0.12, 0.17, and 0.24) are experimented, showing that product gas quality declines with an increase in the equivalence ratio at a specific temperature. Olivine is shown to improve syngas concentration more effectively at 650°C than sand at 750°C and 800°C. At 650°C, olivine has produced nearly the same H₂ concentration (17%) as sand at 750°C (16.9%) and almost the same CO concentration (14.39%) as sand at 800°C (15%) in product gas. across all tested ER values. At higher temperatures, it is expected that olivine will enhance syngas production, yielding more H₂ and CO compared to sand at 750°C and 800°C temperatures.

Preface

This thesis was performed as part of the NORPART project for the master's level exchange program in Engineering, Spring, 2024 at the University of South-Eastern Norway (USN), Porsgrunn. This work primarily aimed at syngas production from air gasification of waste feedstock with natural catalyst, Olivine.

I thankfully acknowledge the support and inspiration that I received from my Supervisor Prof. Britt Margrethe Emilie Moldestad throughout this thesis work. Her clear explanations on the subject and kind nature helped me to learn within a short period of time.

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Nomenclature

Symbol	Description
CO ₂	Carbon Dioxide
CO	Carbon Monoxide
H ₂ O	Water
CH ₄	Methane
N ₂	Nitrogen
H ₂ S	Hydrogen Sulfide
ER	Equivalence Ratio
PSD	Particle Size Distribution
LHV	Lower Heating Value
HHV	Higher Heating Value
CFB	Circulating Fluidized Bed
BFB	Bubbling Fluidized Bed
BFBR	Bubbling Fluidized Bed Reactor
FBG	Fluidized Bed Gasifier
A/F	Air-Fuel Ratio
DFB	Dual Fluidized Bed

1 Introduction

1.1 Background

In the upcoming years, renewable energy technologies are anticipated to grow significantly since they are essential to provide worldwide with clean, affordable, and dependable energy. Gasification of biomass is one of the clean technologies that is particularly interesting for processing biofuels because it can produce clean fuels and generate energy [1]. In addition to producing more affordable power, gasification methods are more effective and environmentally beneficial, and they are easily adaptable to the process of capturing and storing CO₂. According to standard definitions, gasification is the process of reacting solid fuels (such as coal, biomass, and petroleum coke) with oxidants (air, oxygen, steam, and carbon dioxide) at temperatures over 700 degrees Celsius and moderate pressure [2],[3]. A gaseous product is produced in these circumstances, which is mostly made up of syngas (H₂ and CO) and CO₂, as well as CH₄, N₂, H₂S, H₂O, trace sulfur, and other light hydrocarbons and contaminants. Pyrolysis, often referred to as devolatilization, and gasification are the two primary phases of the gasification process; the latter is the step that regulates the rate of the entire conversion process [1].

Wood, agricultural residues, sawdust, straw, manure, paper waste, household wastes, and wastewater are only a few of the diverse components that make up biomass resources from forestry, agriculture, and urban garbage [4]. Modern technologies enable biomass to be converted into solid, liquid, and gaseous states, thereby establishing it as a pure and efficient energy source for all sectors, including transportation fuel, power generation, and heat production. Biomass conversion can occur via either the biochemical pathway or thermochemical pathway. Different conversion techniques such as biomass pyrolysis, gasification, and liquefaction are well-recognized thermochemical conversion processes [5],[6]. Enzymes, bacteria, or other microorganisms are utilized in the biochemical conversion process to transform lignocellulosic biomass into liquid biofuels. The thermochemical route has several advantages over the biochemical route, including feedstock flexibility, faster kinetics, and utilization of the entire biomass. There are three main thermochemical pathways, such as direct combustion, gasification, and pyrolysis [7],[8],[9]. Figure 1.1 shows an overview of biomass and waste conversion technologies.

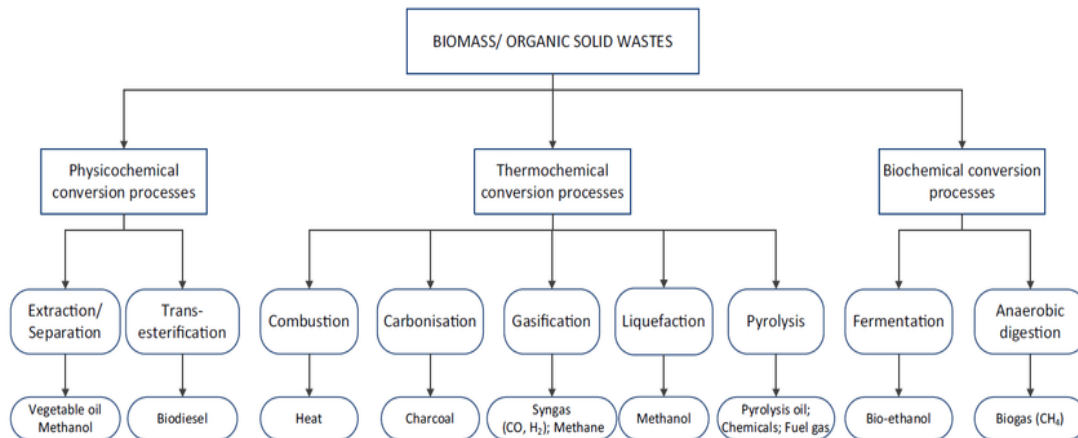


Figure 1.1 Biomass and waste conversion technologies (extracted from [10])

Through gasification biomass or any solid fuel convert into a high-energy gas through partial oxidation at high temperatures. This is done using 20-40% of the stoichiometric air, which is also referred to as the equivalence ratio [11]. The gasification process is influenced by various factors, such as the physical and chemical characteristics of biomass, the type of gasifying agent and its equivalence ratio, the operating temperature, the addition of catalysts, and the type of gasifier used [12]. The product gases from gasification are rich in hydrogen and carbon monoxide that can be utilized for several applications, including the production of valuable chemicals, heat, or power generation.

In recent years, the use of fluidized bed technology for biomass gasification has grown in popularity for a variety of purposes, including the production of syngas and energy [13]. The homogeneous distribution of heat and mass transfer, strong gas-solid mixing, and potential for continuous, large-scale operations make fluidized bed gasification a desirable approach. The bubbling fluidized bed (BFB) is one of the most often utilized types of fluidized bed reactors for gasification processes because it is easy to use and can handle a wide range of feedstock [14].

Since the mid-1980s, there has been an increasing interest in using catalyst in biomass gasification. The progress in this field has been motivated by the necessity to generate a gas product from biomass gasification that is free of tar, as the elimination of tars and the decrease in methane content enhance the economic feasibility of the biomass gasification procedure [15]. Olivine (Mg,Fe_2SiO_4), particles as a natural catalyst is used for gasification of the material in the reactor bed. Olivine particles function as an in-situ tar reduction agent, significantly enhancing the quality of the produced gas in terms of reduced tar content, increased hydrogen volume fraction, and higher syngas yield [16]. Research on catalysts for use in the process is often carried out specifically in relation to gasifier design or biomass feed type. However, the criteria for the catalyst are fundamentally the same and may be summarised as follows [15]:

1. The catalysts must have the ability to remove tars.
2. The catalysts must be capable of reforming methane if the intended product is syngas.
3. The catalysts should ensure that the syngas ratio is appropriate for the intended process.

4. The catalysts should be capable of dealing with deactivation due to carbon fouling and sintering.
5. The catalysts should be readily regenerable.
6. The catalysts must be strong.
7. The catalysts should be cost-effective.

1.2 Objective

The primary objective of this project is to find the minimum reactor operating temperature at which the mixture of coffee and sawdust pellets can be gasified with higher product gas quality using olivine particles. To accomplish the objective the following tasks will be carried out:

1. Feedstock preparation and pelletization of the coffee grounds and sawdust mixture.
2. Preparation and sieving of the bed material sand and olivine particles.
3. Fluidization tests on the cold flow model to identify the flow dynamics behaviour of the bed with the olivine and sand particles.
4. Calibrate pellets feed rate via screw conveyors.
5. Gasification experiments with sand and olivine particles at different air-to-fuel ratio
6. Measure pressure, temperature and monitor reactor operating conditions throughout the operation.
7. Analysis of the collected samples in an offline GC chromatography.
8. Estimate the amount of unconverted carbon for each of the gasification tests.

1.3 Overview and Scope of thesis

Syngas production from biomass gasification is economically viable. The product gases from gasification are rich in hydrogen and carbon monoxide that can be utilized for several applications. Product gas can be transformed into electrical energy and thermal energy through the utilization of internal combustion engines, gas turbines, and fuel cells [17]. The waste feedstock pelletization process executed utilizing a laboratory-scale pelletizer and gasification experiments conducted using a 20 kW bubbling fluidized bed (BFB) gasifier. The waste pellets are composed of a blend of coffee grounds and sawdust. Natural olivine was employed as the bed material in this gasification experiment. Gasifier performance under varying operating conditions was assessed. The product gas composition at different operating analyzed through offline gas chromatography (GC).

2 Literature Review

2.1 Pelletization

Biomass pelletization is the process of densification of raw biomass material into an energy-dense, uniformly shaped small cylindrical pellets by forcing the biomass material under pressure and temperature through a pellet-making machine consisting of a die and rollers arrangement. Pelletization has been shown to improve the thermal efficiency and storage capacity. The use of biomass for biofuel production has been restricted due to some inherent properties of the material, including its large volume, low density, tendency to absorb water, high volatility, high moisture content, low energy content, and lack of uniformity. Low density and bulky biomass require significant storage capacity and costly transportation. Densifying biomass increases its bulk densities, resulting in reduced transportation costs and enabling long-term storage [18]. Figure 2.1 shows an overview of biomass pellet production process.

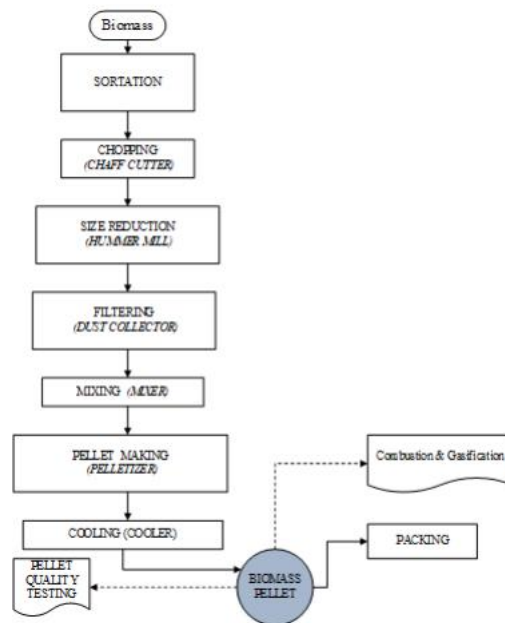


Figure 2.1 Pellet production process [19]

Wood pellet biomass components differ from traditional fuels by utilizing a mix of agricultural waste, biomass, and other additives to create a more environmentally friendly and efficient fuel source. Global pellet production is expected to reach 46.4 million tons in 2022. Europe produces the majority of wood pellets (55% globally), followed by the Americas (31%) [20]. Figure 2.2 shows the production of wood pellets globally.

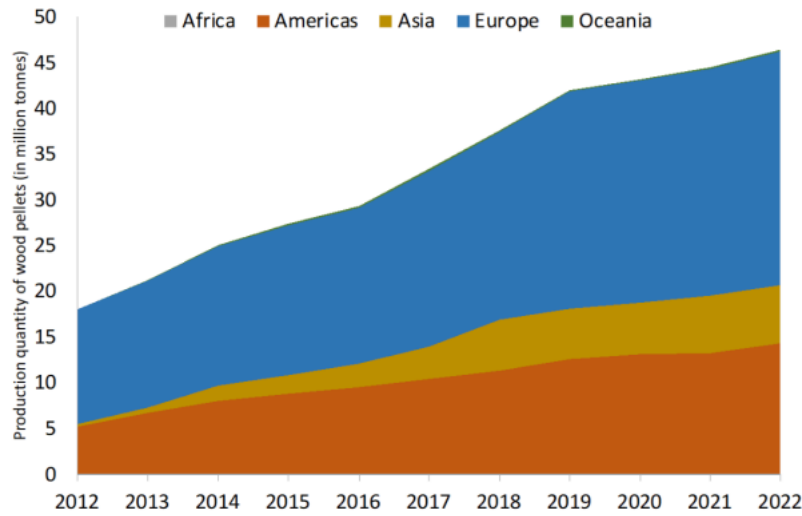


Figure 2.2 Wood pellets production globally [20]

Unlike traditional fuels, biomass pellet fuels incorporate various raw materials like agricultural waste, wood chips, straw, coal powder, and combustion improvers to enhance combustion efficiency and reduce environmental impact. These components are carefully selected to increase the carbon content, prolong combustion time, and enhance the calorific value of the pellets, making them a sustainable alternative to conventional fuels. By effectively utilizing waste biomass and incorporating additives like graphite powder, the biomass pellet fuels not only reduce air pollution but also ensure efficient treatment of biomass resources, thereby increasing their recycling value and environmental friendliness. Biomass pellets are made of sawdust, forestry waste and crop straws [21]. Figure 2.3 shows the composition of biomass feedstock types, with solid biofuels comprising 86%, followed by smaller percentages of industrial waste, municipal waste, liquid biofuels, and biogases, illustrating their use in producing biomass pellets and briquettes for energy applications.

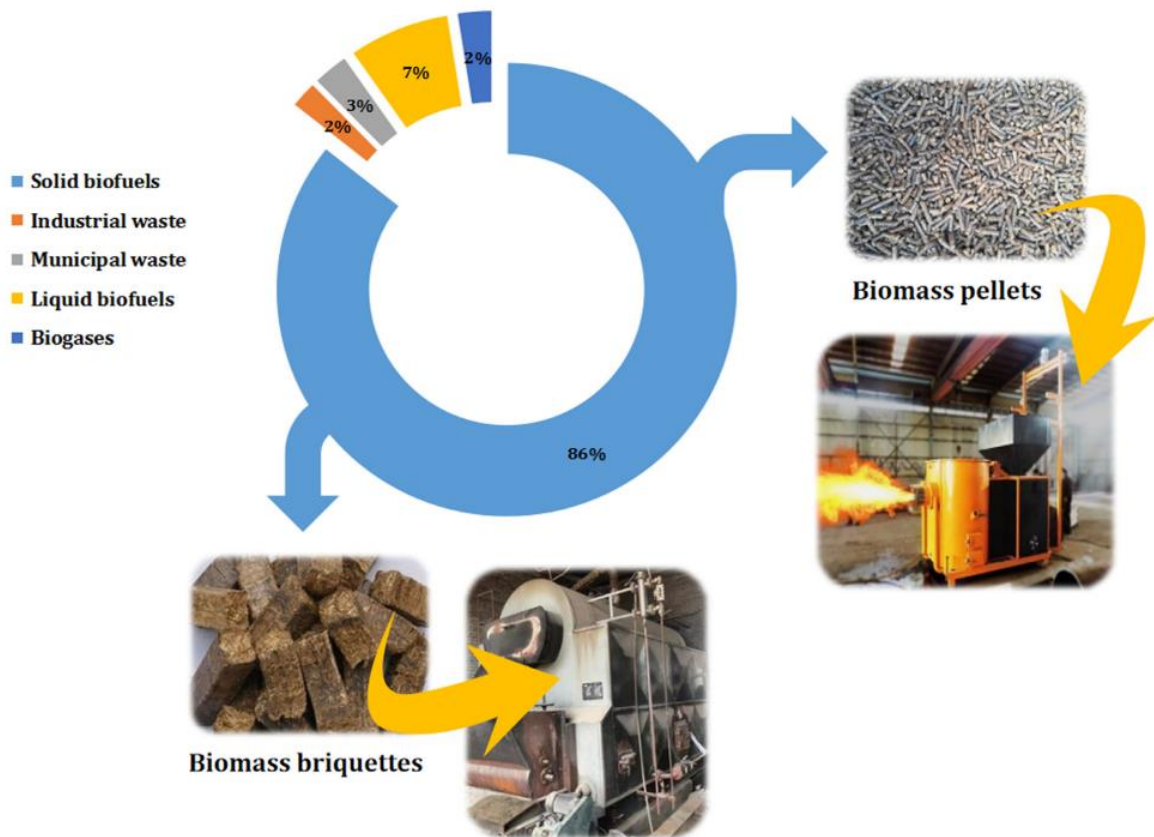


Figure 2.3 Global biomass fuel supply and share of biomass solid fuels in biofuel [22],[23]

2.1.1 Pelletization process parameters

Biomass pelletization parameters include factors such as moisture content, particle size, temperature, and pressure, which significantly influence the quality and properties of the produced pellets. Studies have shown that optimizing these parameters is crucial for enhancing pellet durability, compressive strength, bulk density, and energy content. Research on various biomass sources like *Khaya senegalensis*, microalgae, apple tree wood chips, corn cobs, sunflower seed husks, soybean straw, and cotton stalk has highlighted the importance of parameters like temperature, pressure, and moisture content in achieving high-quality pellets [24],[25],[26].

2.1.1.1 Moisture Content

The net calorific value and combustion efficiency are affected by the moisture content [9]. Pellets that have a high moisture content experience dry matter loss during storage and transportation and are also prone to early decomposition. If pellet storage is not done appropriately, it may cause the pellets to deteriorate or, absorbing humidity from the environment which might decrease the heating value of the pellets [27]. Typically, biomass with a high moisture content is dried in the drying zone prior to being used in gasification [28].

Conversely, if the moisture content exceeds 23%, compaction becomes challenging, leading to soft pellets with excessive moisture (beyond the standard limit of 10%) and the formation of cracks on the pellet surface. An ideal moisture content range for a typical biomass pelletization process is between 10% and 15% [9]. A high-quality pellet should be dry, hard, durable, and with low ash content [29].

2.1.1.2 Binder

The addition of a binder may be necessary for biomass materials with a lower content of lignin, protein, starch, etc. in order to improve binding properties and pellet quality (such as density, strength and hardness) by encouraging strong inter particle bonding and lowering energy consumption. Protein and lignin are chemical components that can improve the pelleting properties of biomass powders. Lignin, with a low melting point of 140°C, enhances the binding characteristics of densified pellets during preheating. When heated, lignin becomes soft and sometimes melts, exhibiting thermosetting properties. The cost and environmental friendliness of a binder must be taken into account while choosing the right one [30]. Pellet binders are frequently used to enhance the properties of pellet thermal conversion [31]. Protein and lignin are chemical components that can improve the pelleting properties of biomass powders. Lignin, with a low melting point of 140°C, enhances the binding characteristics of densified pellets during preheating. When heated, lignin becomes soft and sometimes melts, exhibiting thermosetting properties. Protein also acts as a binding agent during compaction [32].

2.1.1.3 Die Temperature

Temperature affects mechanical properties of biomass pellets during pelletization. The die temperature influences on the durability and density of the biomass pellets. Frictional heat during pelletization indirectly controls the die temperature. Commercial pellet producers use the preheating technique to form high-quality products because the die temperature is another important controlling parameter and because it reduces the specific energy requirement and increases throughput [7].

2.1.1.4 Particle size

In the process of generating biomass pellets, particle size matters greatly because it has major effects on the pore size, total surface area, and points for inter-particle bonding, all of which are necessary to produce higher-quality biomass pellets [33]. Smaller particles fill in the gaps created by larger particles during compaction, improving the pelletization process and producing denser, stronger, and longer-lasting pellets [34]. Smaller particles (such as 0.25–1 mm) provide for improved heat absorption during compaction and a higher surface area for the adsorption of moisture content during conditioning, which improves the binding of biomass particles. In addition, in dry seasons or regions, small particles quickly dry up, which makes pelletizing difficult. The best particle size selection criteria depend on the biomass types and the densification method. The ideal level of particle sizes should be chosen to create higher-quality biomass pellet [35].

2.1.2 Advantages of Pellets

The primary advantages of pelletizing biomass are: A higher energy density, lower transportation and storage costs, combined with standardized sizes and composition, which allows automatic feeding in domestic and industrial sized boilers [36].

2.1.3 Application of biomass pellets

Biomass pellets are used for residential heat and industrial power. Domestic pellets must meet stricter standards than industrial pellets. Domestic heating accounts for 64% of the EU pellet market, with medium-sized boilers (>50 kW) showing the most growth potential. Industrial use of wood pellets for power production in dedicated biomass firing or coal-biomass co firing power plants is concentrated in the UK, Belgium, and The Netherlands, while Scandinavian and German countries use them in combined power and heat generation plants [37]. Biomass pellets find a wide range of applications, primarily as a source of renewable energy. Biomass pellets are frequently utilized in domestic and industrial boilers, as well as power plants, to generate heat and energy. Because of their effectiveness and low emissions, pellet stoves and boilers are well-liked options for heating spaces in homes and businesses. Industries utilize biomass pellets for additional fuel source during manufacturing or as a source of heat for drying procedures. Biomass pellets are used in combined heat and power systems to simultaneously produce energy and usable heat.

2.2 Gasification

Gasification is a thermal process that transforms carbonaceous elements, such as organic or fossil-based substances, into carbon monoxide, hydrogen, and carbon dioxide. Being an efficient waste-to-energy method with higher energy recovery, the technology holds the potential to revolutionize the energy sector by providing an eco-friendly approach to energy generation using various sources with low or negative carbon content, such as high sulfur fuel oil, petroleum coke, coal, residential, industrial, and biomass wastes [38],[39]. Gasification history dates back to around 1881 when producer gas was first used in internal combustion engines, known as suction gas or town gas, evolving into modern sustainable energy systems [40]. Figure 2.4 shows the timeline highlights significant milestones in the history of gasification, starting from the discovery of gas from coal in 1659 to advanced biomass gasification projects in 2001.

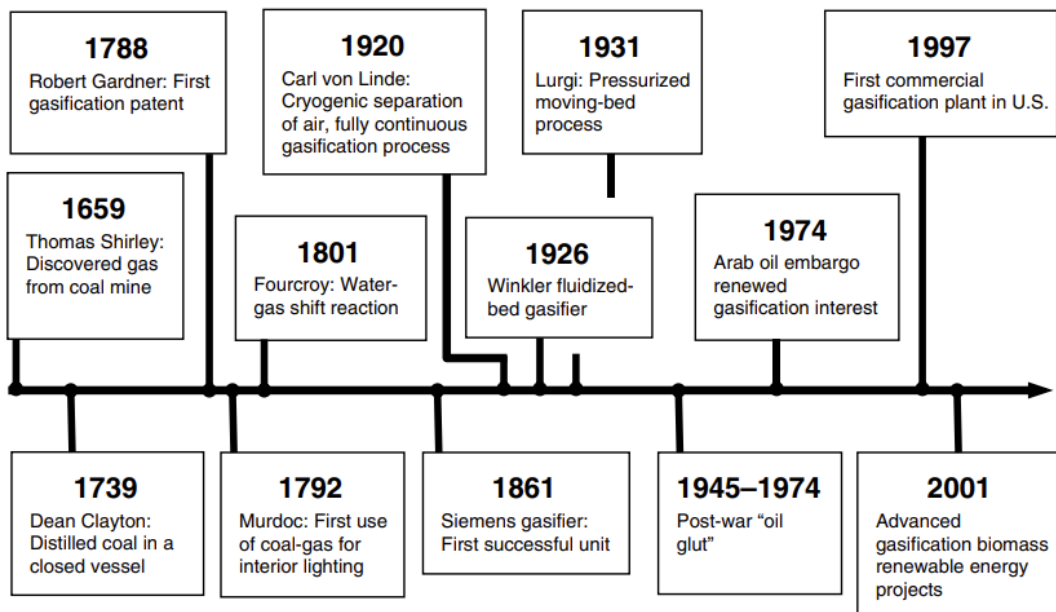


Figure 2.4 Milestones in gasification development (Adapted from [41])

In valorizing biomass wastes, it reduces the environmental impact of waste treatment processes like incineration and landfill. The produced gas, also called the synthesis gas or syngas, can substitute natural gas for electricity generation, used as a vehicle fuel with minimal adjustments to engines when combined with air, or serve as a crucial feedstock for chemical and liquid fuel production. Use of synthesis gas for such purposes can lower the carbon footprint because energy has been generated from materials with low or negative carbon content, thus potentially reducing the greenhouse effect and global warming.

As has been mentioned, gasification involves a thermochemical process that converts solid carbonaceous materials into syngas, biochar, ash, and tars in the presence of a gasifying agent (such as air, steam, or oxygen) at high temperatures. While the technology exhibits variations, leading to a varied final product composition, it generally consists of four key technical components: the atmospheric gasification reactor, which controls oxygen or air content, internal and external heating mechanisms, reactor design, and operating temperature [42]. The process involves introducing dry, finely divided raw materials into the reactor chamber and subjecting them to high temperatures, pressure, and either an oxygen-rich or oxygen-poor environment. Thermochemical conversion undergoes a few stages, namely, drying, pyrolysis, combustion, and reduction. Figure 2.5 illustrates the biomass gasification process, starting from biomass feedstock pre-treatment (physical, chemical, or biological) to various types of gasifiers, producing crude syngas which is then cleaned and conditioned to generate syngas for further applications like Fischer-Tropsch synthesis, synthetic natural gas, hydrogen, and other catalytic syntheses.

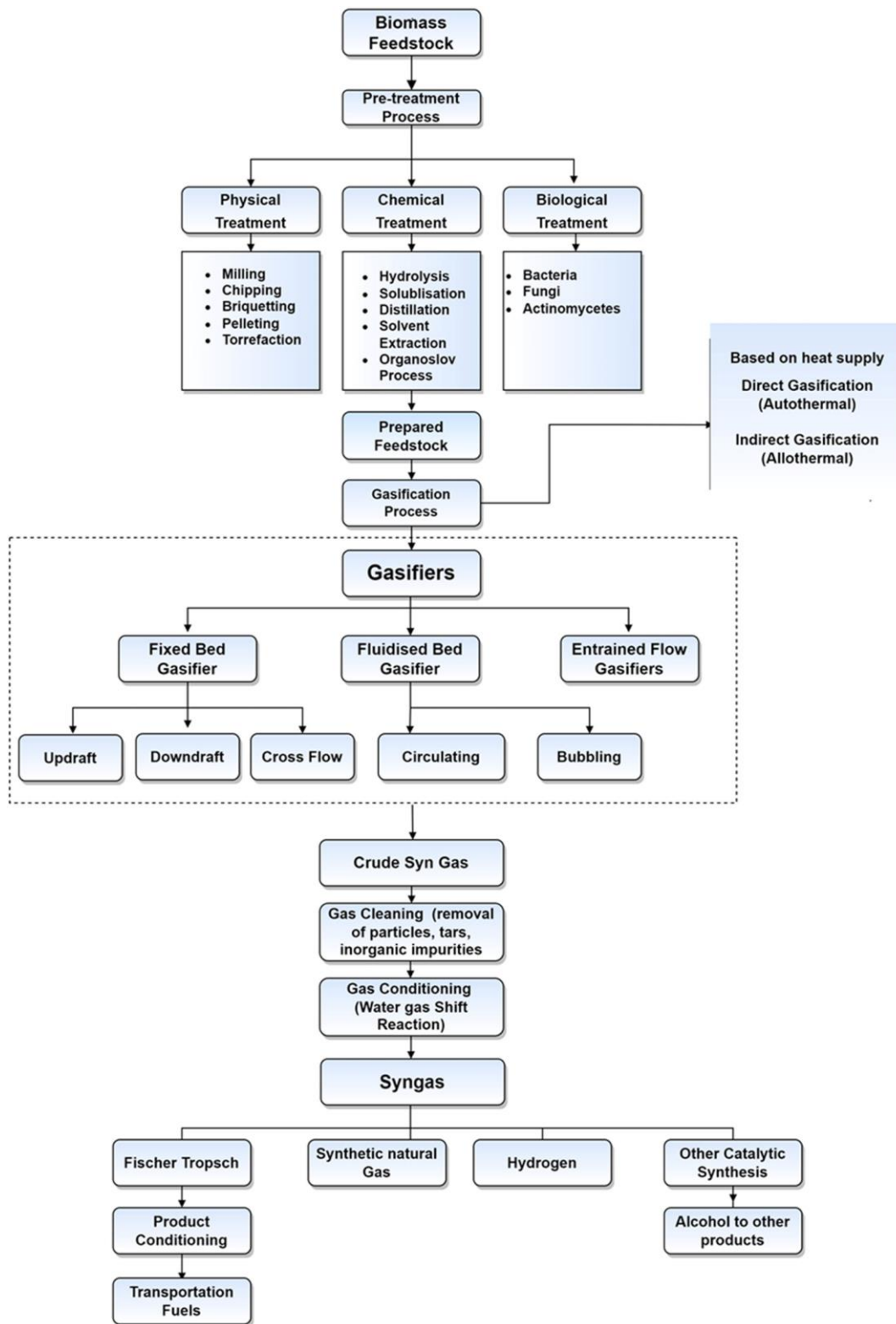


Figure 2.5 Flow diagram of technologies and process for gasification [43]

2.2.1 Gasification operation

2.2.1.1 Drying zone:

During the drying stage, which occurs at temperatures between approximately 100°C and 150°C, compounds with low boiling points, including the bounded water of the biomass evaporate endothermically. A low temperature in this zone prevents the initiation of any chemical reaction thus no decomposition occurs in this zone [44]. Biomass feedstock with a moisture content of less than 15% is suitable for gasification applications. This stage is crucial for preventing water vapor from accumulating in the syngas storage container which can reduce the calorific value of the syngas [45].

2.2.1.2 Pyrolysis zone:

The next stage of gasification is pyrolysis. The thermal breakdown of biomass occurs in the absence of oxygen. Volatile substances vaporizing inside a solid carbonaceous material in the heat source, resulting in ash and char residue. The raw material contains both hydrogen and oxygen, which serve as building blocks for the different gas compositions that are created during pyrolysis. Light gases such as CO, H₂, CH₄, CO₂, NH₃, and H₂O, as well as tar (condensed hydrocarbon vapour) and char (residue left over from the breakdown process), are formed as a result of the previously stated processes. A number of factors, including the feedstock's pre-gasification composition and residue structure, as well as the temperature, pressure, and heating rate enforced by a particular kind of reactor, influence the chemical contents and qualities released during decomposition [46],[47].

2.2.1.3 Combustion zone:

After pyrolysis, the gasifier will go through exothermic combustion, frequently referred to as the oxidation stage. This is when the gasifying agent utilizes the products of pyrolysis. This stage produces the necessary heat for endothermic processes [48]. During the process of combustion, the water-gas transition reaction transforms the gases H₂O and CO into the gases H₂ and CO₂ [49].

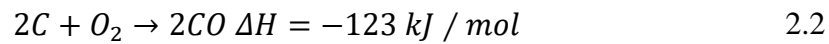
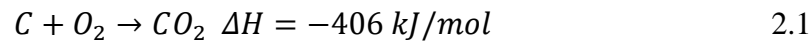
2.2.1.4 Reduction zone

Reduction processes generate flammable gases such as H₂, CO, and CH₄. The four main reactions involved are shift conversion, Boudouard reaction, water-gas reaction, and methanation [50]. The outlet gas from the gasifier is influenced by the characteristics of char formed during the pyrolysis step. Typically, the reactivity of the char determines the speed at which the reduction reaction occurs, and thus, the residence time of the gasification process. Several variables affect the gasification reactivity of chars, such as the rate at which they are heated, the temperature at which pyrolysis occurs, the presence of inorganic components, and the pressure during pyrolysis [51].

2.2.2 Gasification reactions

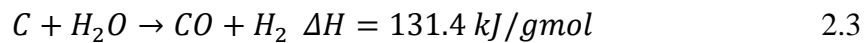
The following chemical reaction can be used to express the mechanisms of biomass gasification [52] :

- **Oxidation zone:** Partial combustion of char and volatiles, producing heat and generating producer gas.

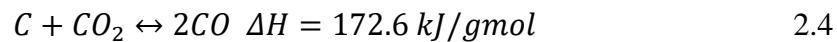


- **Reduction zone:** The reduction zone is where the gases and carbon from the oxidation zone are reduced, resulting in the production of a combustible fuel gas.

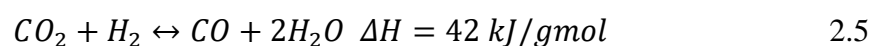
Water-gas reaction: This reaction involves carbon (C) reacting with water vapor (H₂O) to produce carbon monoxide (CO) and hydrogen gas (H₂). The reaction is endothermic, meaning it absorbs heat.



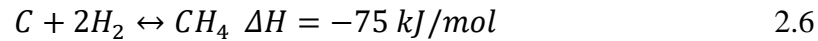
Boudouard reaction: The forward Boudouard reaction, commonly known as char gasification ($C + CO \rightarrow 2CO$), is a potential approach for CO₂ recycling. This process exhibits a significant endothermic nature.



Water-gas shift reaction: The water-gas shift reaction is a moderately exothermic process where carbon monoxide reacts with steam to produce carbon dioxide and hydrogen.



Methane formation reaction: The methanation reaction in the reduction zone of a gasifier is vital for producing methane, an essential fuel gas. Its exothermic nature also helps maintain the necessary thermal conditions for efficient gasification.



2.2.3 Types of Gasifiers

The selection of gasifier type and size is contingent upon various factors, such as product demand, moisture content, and fuel availability. The following types are notable:

2.2.3.1 Fixed Bed and Moving Bed Gasifiers:

Fixed bed gasifiers, known for their straightforward design and operational ease, dominate commercial applications. In moving bed gasifiers, fuel descends through the gasifier in a plug-like manner. Operating pressures typically range from 0 to 70 bars. Gas composition in fixed bed gasifiers typically comprises 3–5% CH₄, 10–15% CO₂, 10–15% CO, 15–20% H₂, and 40–50% N₂ [28].

2.2.3.2 Updraft Gasifiers

These gasifiers, considered among the earliest and simplest types, feature gas entering from the bottom of the system, facilitating a counter-current flow. Solid fuel is introduced from the upper part, while resulting gas exits from the top. The upward movement of hot gas, low in oxygen content, transfers heat to various regions, leading to drying, devolatilization, gasification, and combustion reactions. Despite advantages like simple structure, low investment cost, and high thermal efficiency, updraft gasifiers encounter challenges such as low synthesis gas efficiency, extended engine start-up time, and tar sensitivity [42].

2.2.3.3 Downdraft Gasifiers

This type of gasifier is employed to gasify fuels with high volatility, such as wood and biomass. [2]. In contrast to updraft gasifiers, the gasifying agent is introduced into the combustion zone, specifically in the middle part. Biomass is sent from the upper part to the drying portion, where the moisture content is reduced. The solid fuel is transformed into char and gases as it moves through the pyrolysis zone. The gasifying agent is introduced, and the gases are ignited. The primary objective of controlling the gasification temperature is achieved in this zone, after which the biomass progresses onto the reduction zone. The high temperature in the gasifier output section facilitates low tar production (<5.0 g/Nm). Due to the co-current direction of biomass flow and gas in this gasifier, it is referred to as a "Co-Current Gasifier." [42]

2.2.3.4 Cross-draft Gasifiers

In a cross-draft gasifier with the simplest structure, air is supplied from the side while the biomass is introduced into the upper regions of the reactor and the gases are drawn from the opposite side of the unit to the air inlet at the same level (see figure 2.6) [49]. The air is supplied at high velocity to produce a hearth, in which partial combustion zones is created due to char part burning and temperatures higher than 1500°C can be reached. This forwards the heat to the pyrolysis zone. Gasification reactions are allowed to proceed gradually, which makes for a synthesis gas with high CO content, low H₂ and CH₄ content, high tar levels. The cross draft gasifier shows excellent response to load, flexible gas generation, short start-up time, good ash-insulating effect, and is amenable to dry air blowing. Low reactor heights are adequate in this gasifier configuration, and they are used in small scale units. However, carbon dioxide reduction is weak, and the reactor shows low thermal efficiency because the exit gas leaves the reactor at high temperatures. This type of gasifier also cannot be scaled up [42].

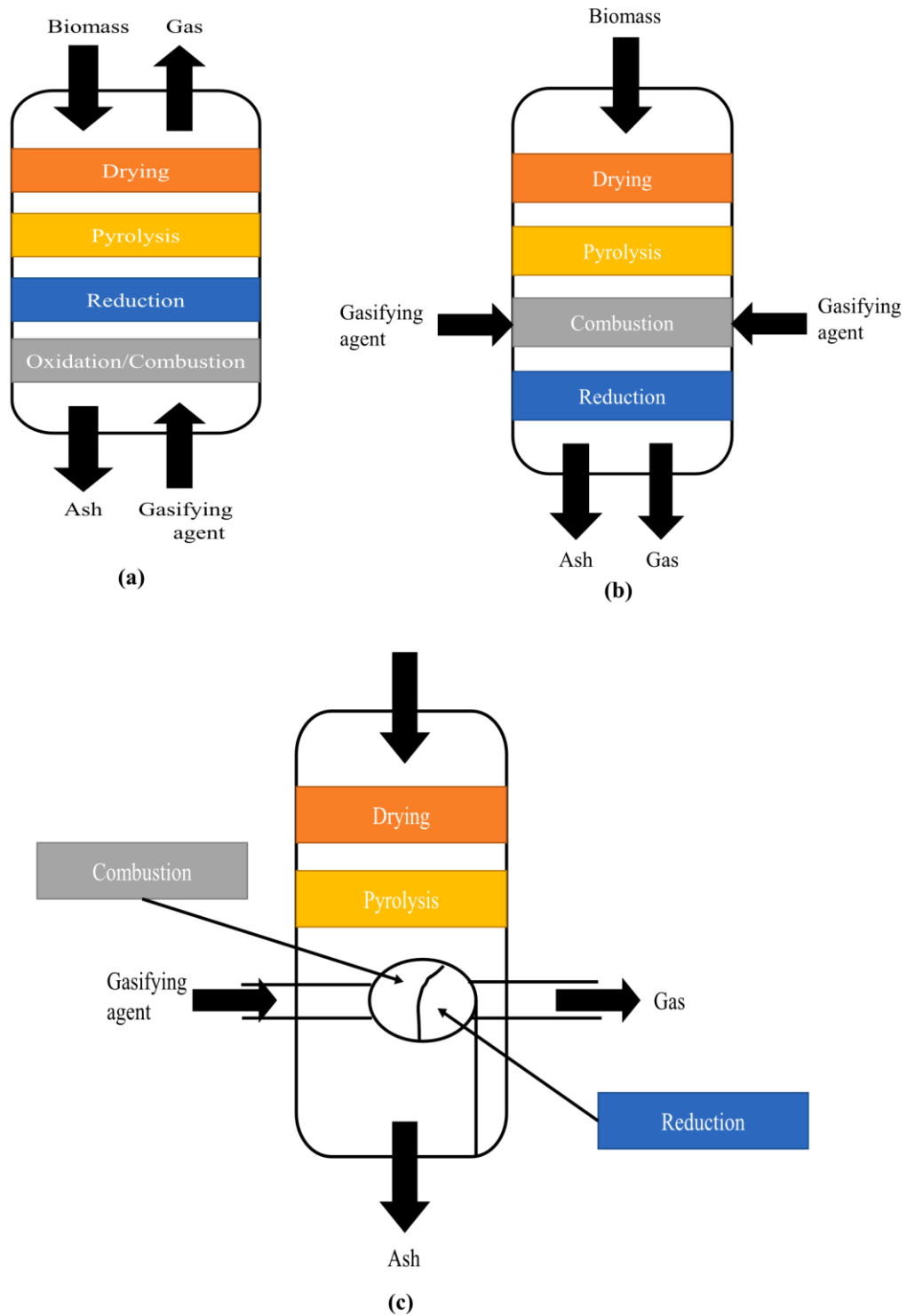


Figure 2.6 a. updraft gasifier b. downdraft gasifier c. cross-draft gasifier [53]

2.2.3.5 Fluidized Bed Gasifiers

A fluidized bed works under the principle of fluidization, where both fuel and inert materials act like a fluid due to a high-velocity fluidization medium. The fluidization medium can be a mixture of steam, air, or steam and oxygen. Silica sand is often used as the bed material, but other bulk solids bearing catalytic properties like olivine sand and dolomite, are also common. Fluidized bed gasifiers are known for their high heat and mass transfer rates and excellent solid mixing, resulting in uniform high reaction rates and temperatures within the bed.

Fluidized bed gasifiers/reactors are relatively more effective due to their superior mixing capabilities, high mass and heat transfer rates, uniform temperature, and broad range of applications. On account of their large thermal inertia and outstanding gas-solid mixing characteristics, the performance of the FBG is relatively unaffected by the quality of the feedstock [54]. Two configurations of the FBGs have been developed and they differ in their heat transfer modes and fluid dynamics: bubbling fluidized bed gasifiers (BFB) and circulating fluidized bed gasifiers (CFB) [55]. Figure 2.7 shows the bubbling fluidized bed gasifier and circulating fluidised bed gasifier.

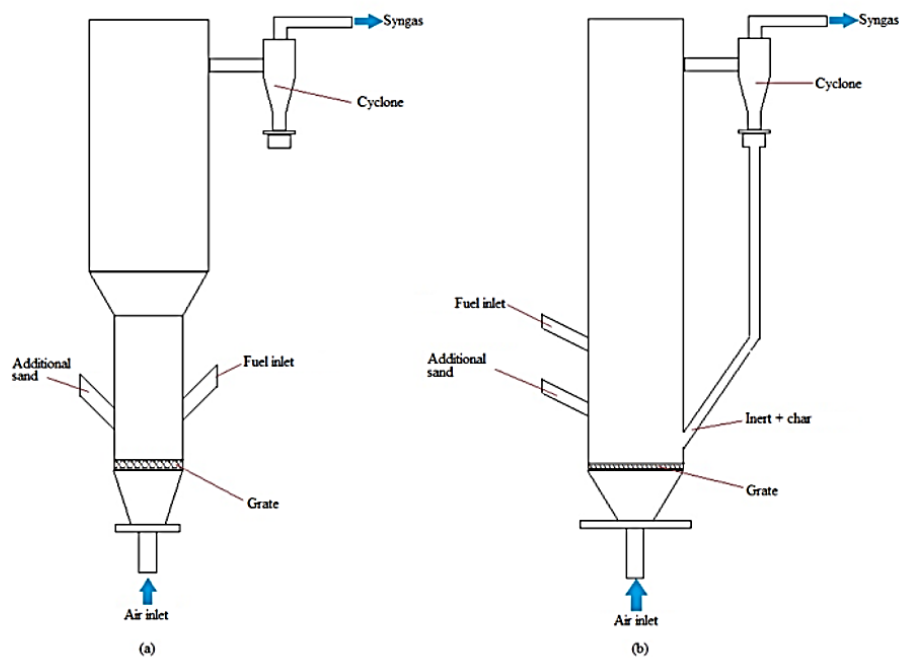


Figure 2.7 a. Bubbling fluidized bed gasifier b. Circulating fluidised bed gasifier [56]

2.2.3.6 Bubbling Fluidized Bed Gasifier

It has a container at the bottom and a grate where air flows through. Finely ground biomass is placed on the grate and transferred into a hot fluidized sand bed by recycling the gaseous product. It is observed that imparting catalytic activity to the bed material shows a significant enhancement in the conversion rate of tar [57]. In these reactors, the gasifying medium moves

upward through the bed at a low velocity (<1 m/s) to facilitate fluidization and maintain the gas bubble mixture. As particles reach the top of the bed, the cross-sectional area expands, reducing the velocity and causing the particles to fall back into the bed. This process promotes particle formation, necessitating the use of multiple cyclone separators at the reactor's exit to manage particulates. [58] Ruiz et al. reported that regulating the steam flow at 1.26 kg/h can produce a low fluidization velocity of 0.18 m/s [59]. This reactor type is able to convert biomass feedstock containing high ash and shows better flexibility over fuel processing and loading [60].

2.2.3.7 Circulating Bed Gasifier

This type of FBG has higher fluidization velocity ($3.5\text{-}5.5\text{ ms}^{-1}$) than its bubbling counterpart. The solids flow outside the main body of the reactor and are recycled back into it (Figure 2.7). The solids are pushed towards the walls owing to the high inlet velocity of the gasification medium, which can lead to back mixing if not operated optimally. Solids can also accumulate in the recycle zone and create problems in the flow especially if the moisture content is high. Because of the circulation, an ample residence time is offered. High gas yields are typical of this reactor type, and the syngas produced is of high calorific value. Furthermore, despite its overall high cost, it is suitable for large-scale operations and features low tar formation [53].

2.2.4 Operating Parameters for gasification

2.2.4.1 Residence time

Residence time is the average amount of time molecules spend in the reactor. The gasification efficiency increases to a certain extent as residence time increases, but it remains constant after a specific value of residence time increment [61]. Hernandez et al.[62] tested gasification on three types of biomass fuels: grapevine pruning, sawdust, and grape marc. Longer residence time improved the syngas yield, which raised the H₂/CO ratio. However, after reaching 1050°C, the temperature remained steady.

2.2.4.2 Equivalence ratio (ER)

ER is one way for evaluating the air/oxygen flow rate during a gasification process. The ratio of air actually used for gasification to the stoichiometric air demand is known as the equivalency ratio. Stoichiometric combustion is represented by an ER of 1, and pyrolysis alone is implied by an ER of 0. Gasification takes place within these two limits [63]. By increasing the ER, more air is introduced into the gasifier, which speeds up the rate of the oxidation reaction and produces more CO₂ [28]. Less carbon monoxide (CO) can be created in the syngas while producing more carbon dioxide with a higher ER value. Less methane (CH₄) and

hydrogen (H₂) are created when the ER value is lower. High ER values approaching or more than one are typically seen in the combustion step following pyrolysis, whereas low ER values approaching zero are typically encountered in the pyrolysis process. Fuel-lean conditions occur when the amount of air or oxygen carried in the gasification agent (oxidant) is less than the amount of air or oxygen that, according to stoichiometry, is theoretically necessary for the complete combustion of the feedstock (biomass); in this instance, the value of ER is less than 1. However, the value of ER increases to greater than 1 when the amount of air or oxygen transported in the gasification agent, as determined by stoichiometry, is less than the amount theoretically needed for the complete combustion of the feedstock (biomass); this is referred to as fuel-rich circumstances. ER stands for actual oxygen/air in the oxidant/stoichiometric oxygen/air. Pyrolysis has an ER value of zero (ER=0) since it is an oxygen-free process. In order to supply enough air and oxygen for complete oxidation reactions to occur, values of ER in combustion approach or surpass one (ER≥1). However, ER is often between 0.25 and 0.5 for partial oxidation events, such as gasification [64].

2.2.4.3 Gasification temperature

In a gasification system, the system is not always run at the same temperature. Each step of the gasification process may have a different temperature. In general, three classes can be distinguished: low, medium, and high. These classes are characterized by temperatures that fluctuate between 400 and 600 °C, 600 and 900 °C, and 900 °C and above, respectively [65]. Instead of referring to temperature, it is more accurate to use the word "temperature profile" to describe the variations in temperature at different stages. The temperature profile is a crucial operating parameter, regardless of whether the system is auto or allo-thermal operated. The temperature profile in an auto-thermal gasification system is influenced by several factors including the composition, inlet temperature, and chemical energy content of the solid biomass (fuel), the degree of insulation in the gasifier, the residence period, and the equivalence ratio (ER). In an allothermal system, the desired temperature is regulated based on the heat supply. A temperature profile can provide insight into the condition of ash and tar that are produced as a result of a gasification process [66],[67]. In the process of steam gasification, the steam reforming processes are endothermic and necessitate greater temperatures. The problems with raising the gasification temperature are that it requires more energy, which means it costs more and makes more tar [68].

2.2.4.4 Bed material

Bed materials are selected based on the fact of heat transfer, mass transfer and fuel mixing ability so that the reactor can maintain an isothermal behavior and high performance. Thus, bed properties can be assessed to maximize the gasification process and raise the quality of the syngas. This will ensure biomass conversion efficiency and produce low amounts of undesired products like tar and alkali compounds. This can be achieved by carefully choosing appropriate minerals [69].

2.2.4.5 Type of biomass

Proximate analysis gives the composition of the biomass in terms of gross components such as moisture, volatile matter, ash, and fixed carbon. The volatile content of a solid fuel indicates the concentration of organic hydrocarbon content in biomass feedstock [70]. This parameter helps not only to determine the amount of fuel generated but also the ability of the biomass feedstock to be ignited and perform thermal conversion. The effect of volatile content on syngas is on the one hand related to the gasification temperature. When the gasification temperature is high, the volatile content can be secondarily pyrolyzed into small molecule gases such as CO, H₂, CH₄, and so on, which will increase the syngas yield. Ash is a byproduct from the gasification of biomass comprised primarily of inorganic materials that remain after the volatile content of burned biomass. When the ash content is too high, it leads to slagging in the furnace, reduces the biomass gasification reaction, lowers syngas production, and influences syngas quality. High moisture biomass is not appropriate for thermochemical conversion. In general, biomass can be processed in a gasifier with a moisture level below 35%; the ideal moisture percentage should be between 10% and 15%. When the moisture content in the biomass feedstock is too high, it will largely reduce the gasification temperature of the reaction, affect the gasification performance, make the gasification reaction incomplete, and reduce the syngas yield and the concentration of combustible gas [39].

2.2.4.6 Gasification agent

Steam is a more effective gasifying agent regarding hydrogen production and steam does not produce any nitrogen. Conversely, nitrogen will undoubtedly be produced as one of the byproducts of air gasification. Since air is an abundant, it is commonly used as a gasifying agent. Table 2.1 shows the advantages and disadvantages of different gasifying agents used in the gasification process.

Table 2.1 Advantages and Disadvantages of Different Gasifying Agents Used in the Gasification Process [39],[42]:

gasification agents	advantage	disadvantage	gas component
air	cheap gas source, high economy, abundant resources, medium tar generation	with high N ₂ content and low H ₂ volume fraction, the product gas has a low calorific value, and the resulting gas is generally used	CO, CO ₂ , H ₂ , CH ₄ , N ₂ , tar

O2	medium calorific value gas, a small volume of gas, reduced sensible heat loss, improved efficiency, lowest tar content, high volume of combustible components	energy consumption for O2 preparation, high cost, and poor economy	CO, CO2, H2, CH4 , tar
steam	high H2 preparation, high and medium calorific value gas generation, and good gas quality all allows for direct fuel usage	additional equipment is required, increasing system complexity and cost and reducing equipment independence	CO, CO2, H2, CH4, tar
air–steam	combining the advantages of water vapor and air vaporization, the economy is obvious	relatively complex system	CO, CO2, H2, CH4 , tar
H2	the high calorific value of combustible gases	high reaction conditions, not currently applied, still under research	CO, CO2, H2, CH4 , tar

2.2.4.7 Tar Content

Tar is generated as a byproduct during the pyrolysis phase of the gasification process. Because tar contains a high concentration of poly-aromatic and condensable hydrocarbons, including ring aromatics and oxygen-based hydrocarbons, it poses challenges to gasification process equipment and must be either removed or treated. If tar has not been eliminated, it might cause harm to process equipment during gasification or to the appliances that receive the resulting syn gas, such as a turbine. The presence of tar can cause issues such as slagging, clogs, and corrosion in boilers and other equipment, leading to a decrease in the overall effectiveness of the gasification process. Tar can also harm catalysts employed in reforming reactions, ceramic filters utilized for removing particles, and sulphur scrubbers employed for eliminating sulphur in a gasification system. The elimination of tar can be performed using a wet method that involves the use of water [71],[66].

2.2.5 Syngas upgrading

The heating value of syngas is affected by the contaminant present in the gas. Thus, the impurities (char, tar) should be removed to make a cleaner form of syngas. N₂ and CO₂ removal is a vital step for the upgradation of syngas. CO₂ can be removed by two approaches- extraction or reducing reactions to interact with charcoal/tar and partial reduction of CO₂ to generate CO. If pure O₂ or steam can be used as gasifying agent then the removal of N₂ is possible to a great extent [72],[73],[74].

2.3 Fluidization

A brief description of fluidization, different fluidization regimes, minimum fluidization velocity are provided on this chapter.

2.3.1 Principal of fluidization

Fluidization is a process in which granular material behaves like a liquid when suspended in a fluid, such as gas or liquid. This phenomenon occurs when a fluid is directed upwards through a bed of granular material. At a low superficial gas velocity, as illustrated in Figure 2.9, the drag force exerted on the particles is too weak to counteract their weight, keeping the bed in a fixed bed state. When the minimum fluidization velocity, or the critical value of the superficial gas velocity, is reached, the upward drag force equals the downward gravitational force operating on the particles. When the particulates are suspended in the fluid, and the bed is regarded as fluidized [75]. The state of a fluidized bed depends on the fluid flow rate. Due to velocity differences, different regimes are created in fluidized beds [76]. Figure 2.9 illustrates the different fluidization regimes in gas-solid systems.

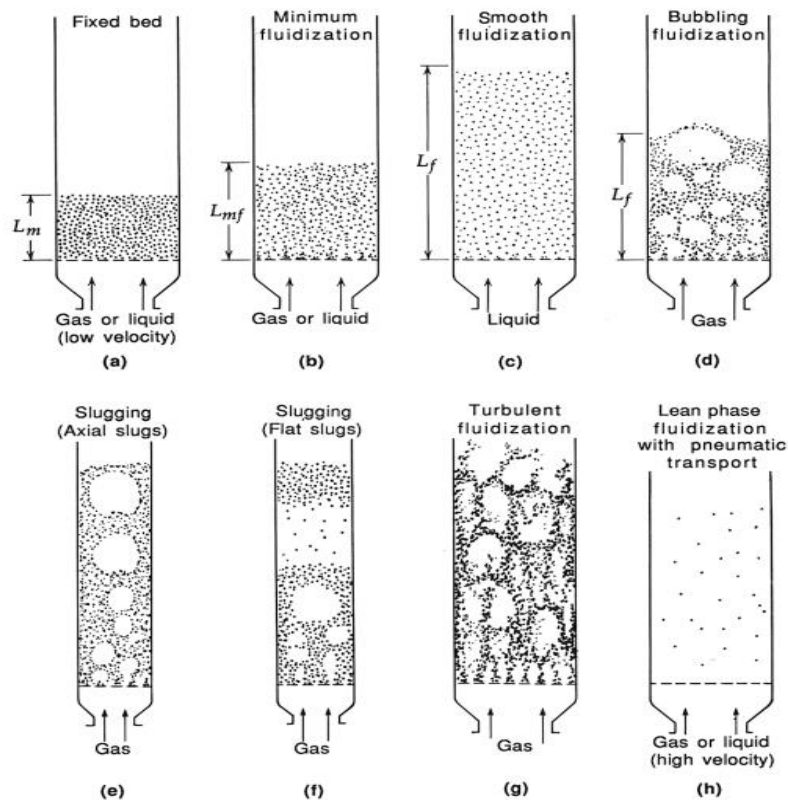


Figure 2.8 Different fluidization regimes in gas-solid systems [77]

2.3.2 Minimum fluidization velocity

Minimum fluidization velocity refers to the transition velocity in which packed bed behavior changes to fluidized bed. It describes the situation in which the pressure drop across the bed is equal to the weight of the bed per unit cross-sectional area. The pressure drop increases linearly with gas velocity in a packed bed until the total drag force on the bed starts to approach the weight of the bed (Figure 2.8). In beds with small diameter (< 6 inches), the effective bed weight is slightly less than calculated because it is partly supported by retaining walls due to friction and by the distributor plate. If the bed is pre-compacted or the bed diameter is small, the pressure drop exhibits a peak value before settling into a largely constant value. For beds with wide particle size distribution, the pressure drop curve is much broader without a distinct point of inflection [78]. Figure 2.8 shows the characteristic pressure drop response from a packed bed to a fluidized where pressure drop (ΔP) is plotted against superficial gas velocity (U).

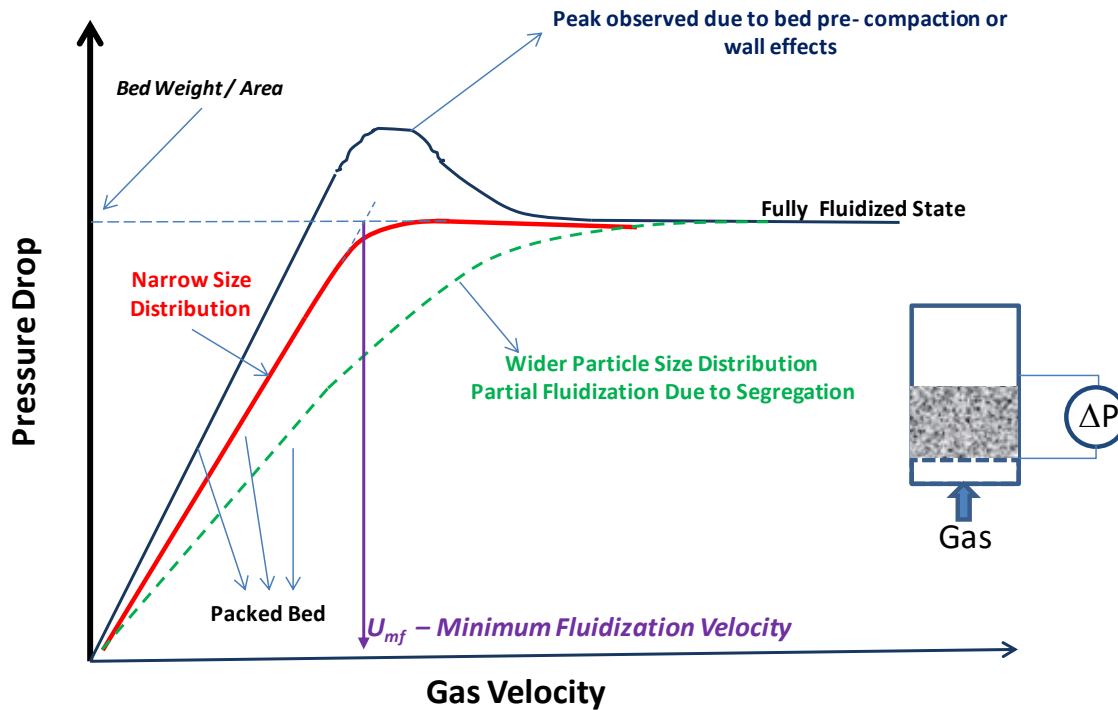


Figure 2.9 Characteristic pressure drop response – packed bed to fluidized bed

The pressure drop can be calculated using the Ergun correlation-

$$\frac{\Delta P}{L} = 150 \frac{(1 - \epsilon)^2}{\epsilon^3} \frac{\mu u_0}{\phi^2 d_p^2} + 1.75 \frac{1 - \epsilon}{\epsilon^3} \frac{\rho_f u_0^2}{\phi d_p} \quad 2.7$$

where d_p , u_0 , ϕ and μ are volume-to-surface mean particle diameter (where diameter of each particle is expressed by the diameter of a sphere of equal volume), superficial fluid velocity (fluid volume flow rate divided by cross section when no particles exist), shape factor (surface area of a sphere of diameter d_p divided by real particle surface area) and viscosity of fluid, respectively [79].

2.4 Olivine as a bed material

Extensive study has been conducted in recent years on catalytic cracking and the advancement of diverse catalysts. Furthermore, many catalysts, including dolomites, olivine, and FCC, have been examined to determine the most effective methods for tar cracking. Additionally, recommendations were made for the optimal process conditions and certain pre-treatment methods to extend the lifespan of the catalyst. Olivine, also known as dolomite, is a naturally occurring mineral that contains magnesium, iron, and silicon in the chemical composition of Fe_2SiO_4 or Mg_2SiO_4 . Natural materials like dolomite, magnesite, limestone, and olivine all possess tar cracking abilities [80]. Olivine possesses the ability to convert tar

because of the presence of magnesite Reports indicate that olivine exhibits superior catalytic activity in tar destruction and mechanical strength at temperatures above 800°C for an extended period of time. This makes olivine a better choice for use in fluidized bed gasifiers compared to dolomite and quartz sand. Catalytically active bed materials have the ability to significantly impact the gas composition and the amount of tar formed in the gas. Olivine has been commonly employed as the standard bed material in fluidized bed gasification, particularly in dual fluidized bed steam gasification, for the last twenty years [81],[82].

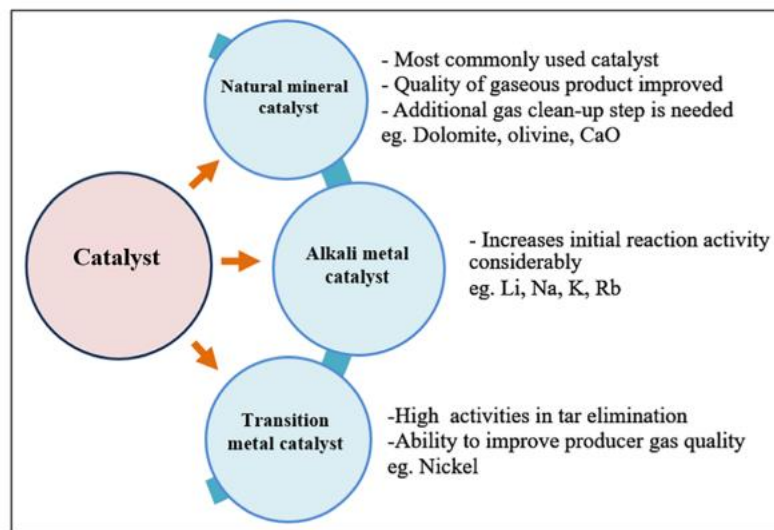


Figure 2.10 Catalyst for biomass gasification [83]

Using catalysts in gasification has several advantages and disadvantages. Catalysts can significantly speed up the gasification reactions. Table 2.2 shows the Advantages and disadvantages of different catalysts employed in gasification.

Table 2.2 Advantages and disadvantages of different catalysts employed in gasification [84]:

Catalyst	Advantages	Disadvantages
Natural	<ul style="list-style-type: none"> - Olivine has a high attrition resistance - Readily available at low cost - It is suitable for use as a bed material in a fluidized bed gasifier - Effective in tar decomposition 	<ul style="list-style-type: none"> - Dolomite is susceptible to attrition as a result of lower mechanical strength - Low activity in tar cracking - Fragmentation of dolomite particle during calcination - Ineffective activity in modifying gaseous hydrocarbon concentrations
Nickel based	<ul style="list-style-type: none"> - High H₂ yield and improved catalytic cracking of tar - High reforming efficiency - Excellent resistance to tar deposition - Efficient catalyst for tar elimination and good product yield 	<ul style="list-style-type: none"> - Costly and affect economic viability - Not suitable as secondary catalyst - Produces large amount of ash - Easily get agglomerated and clogged in the pipes at a higher temperature - CH₄ reforming reaction at ≥ 800 °C
Alkali metal	<ul style="list-style-type: none"> - High reforming efficiency and H₂ yield - More suitable as secondary catalysts and effective for NH₃ reduction - Use of different promoters and support increases the catalytic activity - More than 99% tar conversion efficiency 	<ul style="list-style-type: none"> - Coking is prevalent in Ni catalyst - Suffers significant attrition in fluidized bed - High investment cost and expensive - Susceptible to H₂S poisoning - Loses catalytic activity due to sintering - Deactivation of tar and carbon-containing gas at high temperatures - Use at about 780 °C gives a better lifetime for economical operation

2.4.1 Advantages of olivine

2.4.1.1 Layer formation olivine

Olivine is a magnesium-iron silicate substance that may contain impurities such as Ni and Cr. In a combustion/gasification environment with ash-containing fuels, untreated olivine particles become coated with ash-forming components. An already established layer typically has two morphological features: (1) a homogeneous and melt-like core layer, and (2) a more heterogeneous outer layer [85] The inner layer may consist of two zones: an innermost Ca-rich region surrounding by a Mg-rich region, which is theorized to form as Mg ions are ejected

from the olivine structure as Ca ions are integrated. During the extended operation of a demonstration-scale DFB plant, the development of layers on olivine particles was observed during gasification. Nevertheless, the composition of the inner layer differed greatly from the established composition of the inner layer found in quartz sand. Regarding olivine, the building of the inner layer did not result in an increase in the alkali content within the layer. Instead, it appeared to be dominated by calcium. The presence of a calcium-rich layer on olivine had an impact on the synthesis of methane (CH₄) during the process of dry reforming. On the other hand, raw olivine mainly promoted the production of carbon monoxide (CO) and hydrogen (H₂) [85]. Proper layer formation prevents agglomeration of ash particles, which can disrupt the gasification process. Layers facilitate chemical reactions, improving biomass conversion into syngas and reducing unwanted by-products. Additionally, layers protect the gasifier's internal components from corrosive compounds or excessive wear, extending their lifespan.

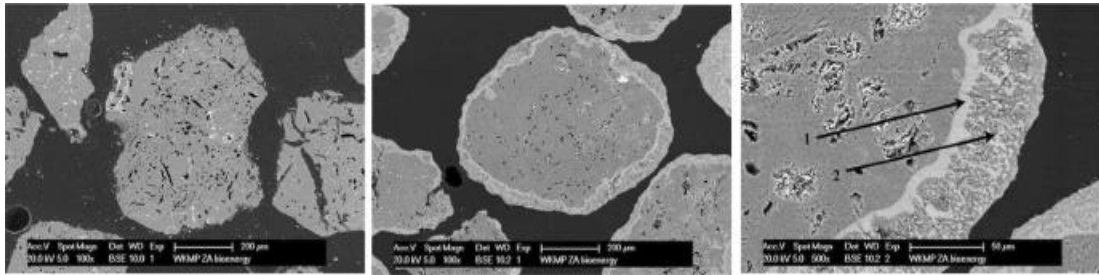


Figure 2.11 EM images of unused calcined olivine (left), used calcined olivine (central) and inner layer (1) and outer catalytic layer (2) [86]

2.4.1.2 Tar cracking ability of olivine

Extensive study has been conducted in recent years on catalytic cracking and the advancements of different catalysts. Furthermore, many catalysts, including dolomites, olivine, and FCC, have been examined to determine the most effective methods for tar cracking. Tars are generated due to partial reaction of biomass and made of a complex range of oxygenated and non-oxygenated organic constituents [87]. Many efforts have been made to remove gasification tar through physical and chemical methods, such as filtration/physical

removal, catalytic cracking , non-catalytic cracking [13].

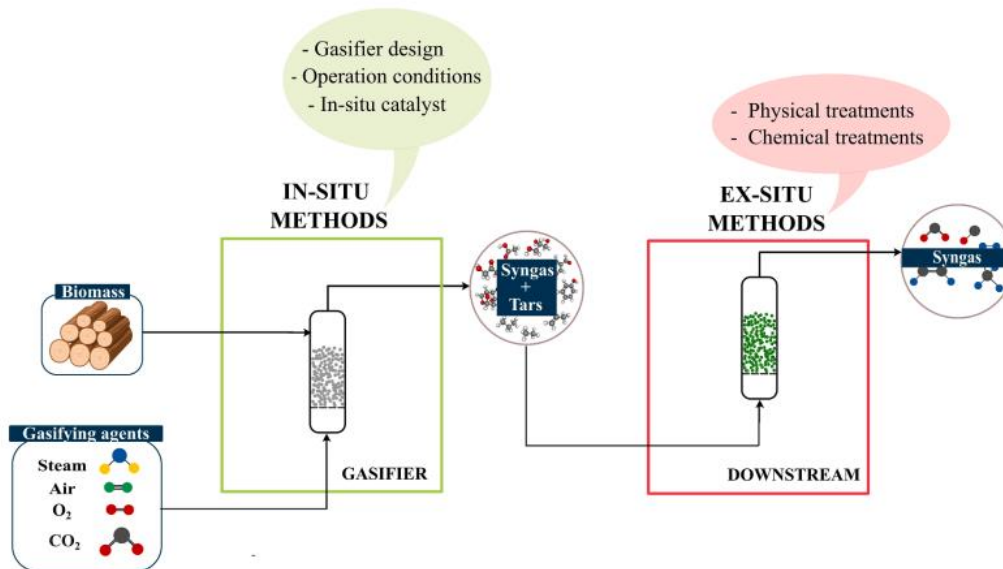


Figure 2.12 Schematic representation of tar removal strategies. Adapted from [88]

Corella et al.[89] employed olivine and dolomite as bed materials in a bubbling bed gasifier, demonstrating the catalytic characteristics of both materials and leading to a decrease in tar content to 5 g/Nm³ and 1.6 g/Nm³, respectively. Another study discovered that olivine materials loaded with iron display a dual reaction, acting as a catalyst for both biomass and tar cracking [90].

2.4.2 Drawbacks of olivine

Olivine transports oxygen across the combustion sides and gasification sides of an indirect gasification system, lowering the lower heating value (LHV) of the product gas [91]. Furthermore, the presence of heavy metals in olivine poses a risk to the environment and complicates its disposal.

3 Methodology

3.1 Sample Preparation

3.1.1 Collection of coffee waste

The coffee waste used in this study was collected from the cafe of the university (University of South-Eastern Norway). The coffee waste collected from the cafe had a high amount of moisture. The sample was spread in a plastic sheet to reduce the moisture and kept in the lab at room temperature. Approximately 2 to 3 days were required to obtain the required moisture content.



Figure 3.1 Coffee waste before drying



Figure 3.2 Coffee Waste after Drying

3.1.2 Detection of moisture content

Different moisture content was observed using moisture detector. Because too much moisture greatly reduces the fuel value. A moisture detector shown in Figure 4.3 was used to measure the required moisture content.



Figure 3.3 Moisture detector

3.1.3 Coffee with 10% Straw

To enhance the strength of coffee waste pellets, barley straw was incorporated as a binding agent due to their inherent low strength. The coffee sample with straw was created by combining the straw with 10% of the coffee waste by weight. Initially, the weight of dried coffee waste was measured, and then, the weight of prepared straw was determined and combined with the coffee waste. An example of a coffee waste with straw is shown in Figure 3.4.



Figure 3.4 Coffee waste mixed with straw

3.2 Pelletizing Process

3.2.1 Coffee pellet production

The process of pellet production was conducted using a flat die-type pellet machine. Biomass is introduced into the machine from the top and forms a layer of product on the die. The pan grinder rollers continuously roll over the layer, causing the biomass to be compacted and forced into the die roller. Enough force was developed to press the biomass through the die. The biomass is compressed even more inside the , resulting in the formation of a cylindrical pellet. This pellet is then cut to the desired length by a breaking-off device. The pellets were conveyed to the output using the discharge mechanism. A single machine was utilized to produce all kinds of pellets for this investigation. The distance between the die and the roller of the pellet machine remained constant at 0.4mm during all the pellet-making procedures. The physical strength of pellets manufactured from samples with varying moisture content was assessed manually, and the optimal moisture concentration was determined based on these observations. Table 3.1 shows the characteristics of coffee pellets.

Table 3.1 Characteristics of pellets

Characteristics	Coffee pellet	Units
Particle density	1100	Kg/m ³
Length	20-30	mm
Diameter	6	mm
Shape	Cylinder	Cylinder



Figure 3.5 Pellet Machine



Figure 3.6 Die and Roller Arrangement



Figure 3.7 Pellets coming out of die

3.3 Gasification Process

3.3.1 Mechanical sieving

Mechanical sieving was used to determine the particle size distribution (PSD) of particles. A test sample was added to a sieving machine. Different sets of mesh wire sieves with the size range of 710, 500, 355, 200 micrometer were used for olivine and 600, 500, 425, 355, 200 micrometer were used for sand materials. The sieving time was 10 min. Sieves of varying diameters were stacked in descending order on a sieving machine. After being loaded with sand and olivine particles, the sieves were securely fastened using locks. A 1.5-meter amplitude was used for 5 minutes of operation on the sieve machine. Following the completion of the screening process, the locks were taken off and the various sized sand particles were divided into various containers. As a bed material, sand particles with a diameter of 355–600 μm and a density of 2650 kg/m^3 were chosen. For another experiment, olivine particles with a diameter of 200–355 μm and a density of 3300 kg/m^3 were chosen. At the end of each test, the sieves were cleaned by blowing compressed air and brushing off the dust.



Sand particles



Sieve arrangements



Olivine particles



Sieve arrangements

Figure 3.8 Mechanical sieving of sand and olivine particles

3.3.2 Experiment on cold bed rig with olivine particle

Experiments were conducted on a cold fluidized bed to determine the minimum fluidization velocity and the velocity where the bubbling fluidized regime starts. Experiments on cold bed was performed with the same size and weight (2.2 kg) of olivine that was used in the biomass gasifier for bed material. The experiments were performed so that the data obtained from the cold bed experiments can be used to study the fluidization behavior of the bed material used in a gasification reactor. The cold bed rig consist of transparent cylinder of height 1.3 meter and a diameter of 0.1 meter. Nine pressure sensors are installed along the height of the cylinder and the distance between each sensors is 0.1 meter. The cylinder is opened to the atmosphere at the top. Two inlets are provided near the base of the reactor which is 0.04 meter below the first sensor. The inlets are on the opposite side of each other. The two inlets are connected with 'T' section to get a single output. Air was sent to the reactor through this single output. There was no air distributor to distribute the air throughout the reactor. The pressure sensors were connected to a labVIEW program, where the pressure data are logged and stored. The program also controls and registers the air flow rates. The olivine particles that was used in gasifier was used for the experiments and air at ambient pressure and temperature was used as fluidizing agent. The gas flow rate was varied stepwise to determine the transition from fixed to fluidized and bubbling bed.



Figure 3.9 Experimental Setup of Cold Bed Rig

3.3.3 Experiment with bed material sand in the gasification reactor

The bubbling fluidized bed reactor of 20KW was used for the gasification process. The pellets made from the pellet machine were allowed to dry for a few days before using it as feed stock for the gasification process. Pellets were first feed to the silo and the two feeding screw arrangements were allowed to run for the calibration process. The calibration was done on the different percentages of rotation of the screw and different time duration of feed rates. After the calibration process all the openings were closed, and the gasification process was carried out. After that, the reactor was filled with 2.2kg of 355-600 μm sand particles. The reactor heaters and the air preheater were switched on when the bed was at fluidization conditions. Once the bed material reached 650°C, the fuel feeding was started and it was kept the same for all experiments. Table 3.2 shows the calibration of feed screw for coffee pellets.

Table 3.2 Calibration of feed screw for pellets

Percentage of rotation	Duration of time of feed rates (minutes)	Mass, kg	Weight of biomass collected kg/h
4%	3	0.25	5
3%	3	0.21	4.2
3%	4	0.26	3.9
3%	3	0.18	3.6
	3.1	0.21	4.064516
	3	0.23	4.6

The reactor heaters were energized in accordance with the airflow to maintain the desired temperature, and the ER was changed. The bed pressure was consistently monitored, which was beneficial in detecting any clinker formation. The gas volume that was collected inside the sampling pipe during the previous sampling was always removed using precautionary measures. The feedstock, which was in the form of pellets, was introduced to the reactor at a specific rotation percentage of the screw once the bed material began to fluidize. The gas samples that were generated during the gasification process were collected at various intervals using a syringe and kept to calm down in order to allow the tar to condense. The samples were given to offline gas chromatography for additional analysis. The gas generated during the gasification process is not suitable for direct release into the environment due to its presence of various hazardous gases, including CO, CO₂, and others. Therefore, it is necessary that the gases are incinerated appropriately prior to their release into the atmosphere.

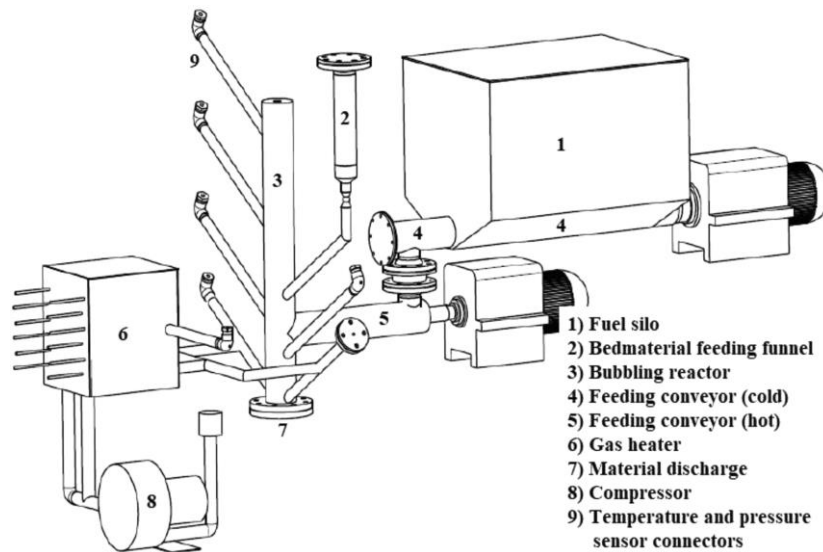


Figure 3.10 Bubbling fluidized bed experimental rig with auxiliary attachments [92]

3.3.4 Experiment with bed material olivine in the gasification reactor

A 20KW bubbling flow fluidized bed reactor was employed for the gasification process. The pellets produced by the pellet machine were left to dry for several days before being used as feedstock for the gasification process. The reactor contained 2.2 kg of olivine particles measuring 200-355 micrometers in size. The reactor heaters and the air preheater were activated while the bed was in a state of fluidization. Once the temperature of the bed material reached 550°C, the process of fuel feeding was initiated and maintained at a constant level throughout all the trials. The bed pressure was continuously monitored, which proved advantageous in detecting any clinker buildup. The gas volume that was collected inside the sample pipe during the previous sampling was consistently eliminated utilizing preventive measures. The pellets, serving as the feedstock, were injected into the reactor at a particular screw rotation 3% once the bed material started to fluidize. The gas samples produced during the gasification process were collected at different time intervals using a syringe and then allowed to cool down to facilitate the condensation of tar. The samples were subjected to offline gas chromatography for further analysis. The gas produced during the gasification process is unsuitable for direct emission into the environment due to the presence of several harmful gases, including as carbon monoxide (CO), carbon dioxide (CO₂), and others. Hence, it is imperative that the gases are adequately burned before being discharged into the atmosphere. Table 3.3 shows the actual air flow rate and ER for different experiments.

Table 3.3 Actual airflow and ER for different experiments

Biomass	Feed rate Kg/h	Stoichiometric air(kg/h)	Actual air flowrate (kg/h)	Equivalence Ratio (ER)
sand	4.06	29.25	3.5	0.119
			5	0.170
			7	0.239
olivine	4.06	29.25	3.5	0.119
			5	0.170



Figure 3.11 Gasifiers used in operation

3.4 Gas Chromatography

The gas samples obtained at regular intervals using a syringe were analyzed for the composition of the various producing gases using gas chromatography (GC). Figure 3.12 shows the gas chromatography machine. When examining gases, columns filled with silica gel were used to identify carbon dioxide, while columns filled with molecular sieve 13X were used to identify nitrogen, oxygen, methane, and carbon monoxide. Helium was used as the carrier gas.

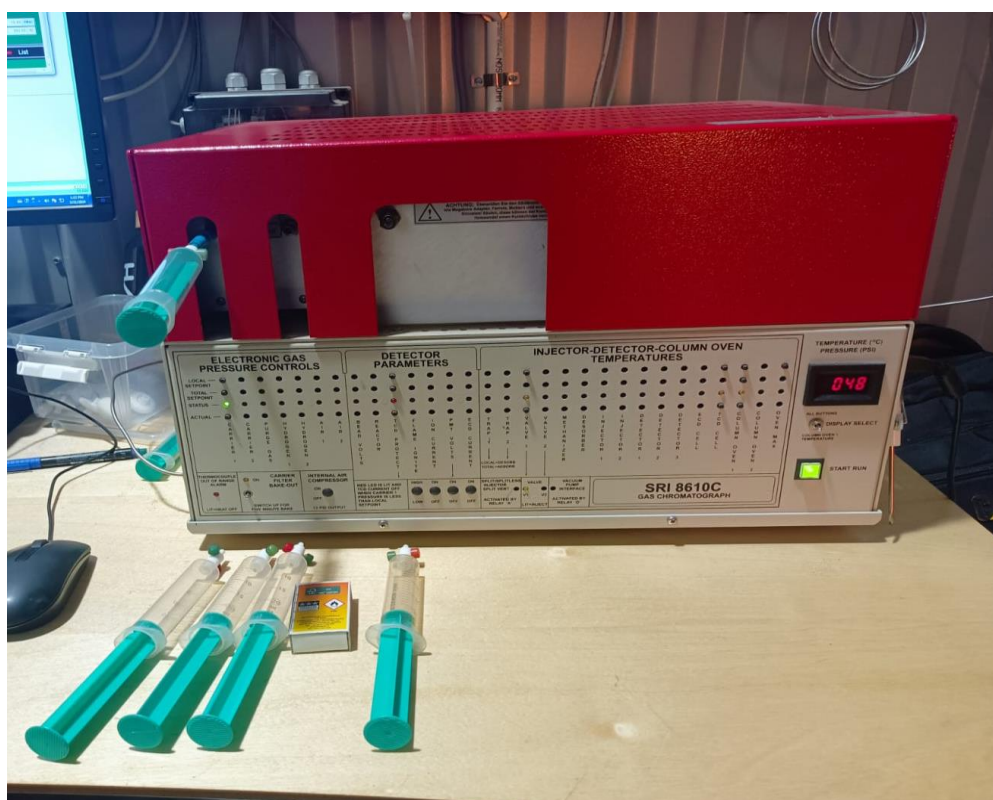


Figure 3.12 Gas Chromatography

4 Result and discussion

The results obtained from the pelletizing process, gasification and gas chromatography are discussed under this chapter.

4.1 Pelletizing Process

4.1.1 Measuring the pellet size

The pellets were 6 mm in diameter and 20-30 mm in length. During the feeding through screw conveyors, pellets were broken and became heterogeneous in size.

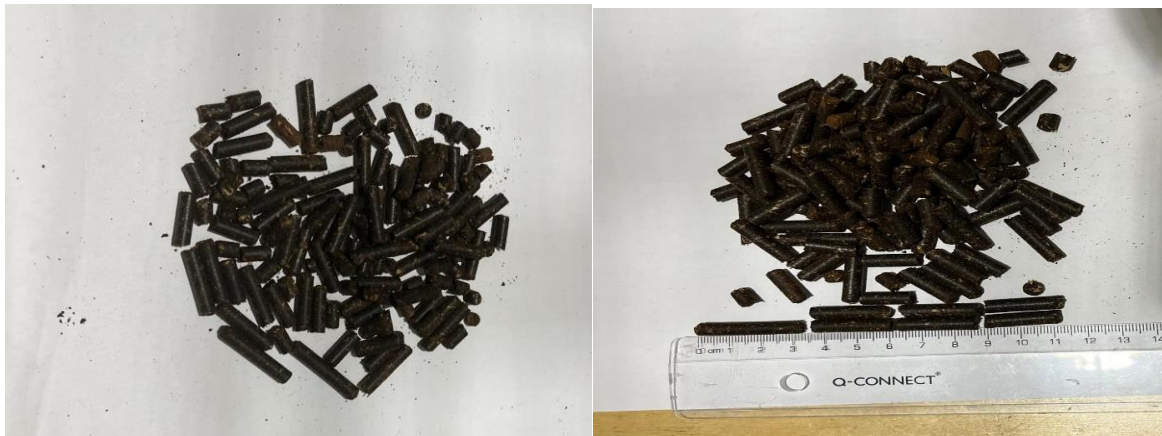


Figure 4.1 Coffee Pellets

4.1.2 Pellets with different moisture content

Since pellet quality is influenced by moisture level, we obtain a variety of pellet characteristics, the most acceptable of which had a moisture content of 9%. It was observed that the quality and strength of the pellets decreased with higher moisture contents of 10% and 13%.



Figure 4.2 Pellets with moisture content of 9%,10% and 13% (from left)

4.2 Mechanical Sieving

4.2.1 Particle size distribution

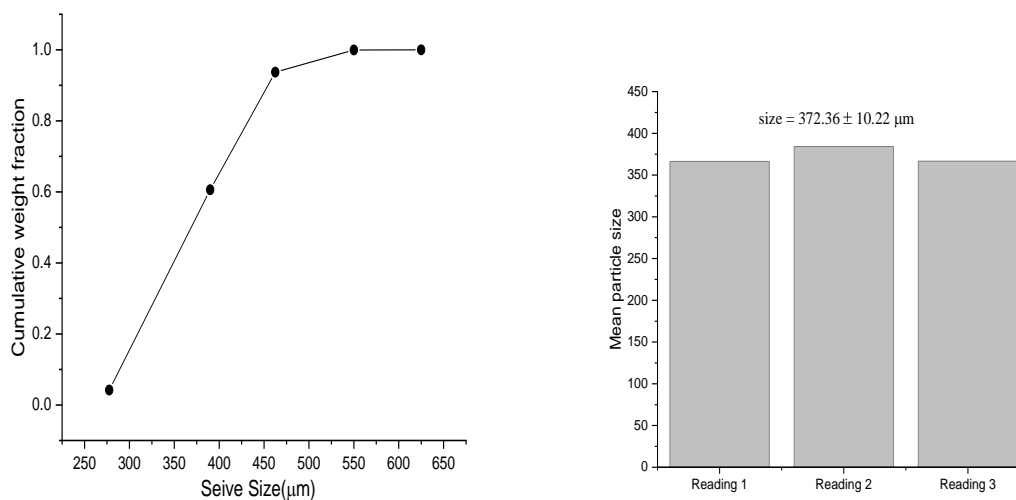


Figure 4.3 Particle size distribution graph of sand particle

Bed material size has an enormous effect on gas composition. After sieving the sand particle and calculating the mean particle diameter, the range of particle size were chosen as 355 – 600 μm. The same procedure was followed for olivine particle and for the ease of comparison with the data of gasification process with bed material sand in a bubbling fluidized bed, the particle range was chosen near the sand particle and that was 200-355 μm. The result is shown in Figure 5.3. and the calculation is added to Appendix A.

4.3 Cold bed experiment

The experiments were performed with olivine to determine the minimum fluidization velocities and the velocities from where the bubbling regime starts. The calculation is added to Appendix B. The result is shown in Figure 4.4. The figure consists of the data obtained from experiments with olivine. The result is presented as pressure drop versus superficial gas velocity. The minimum fluidization velocity refers to the velocity at which the pressure drop reaches its highest value. From the experiment, the olivine has a minimum fluidization velocity of 0.043 m/sec.

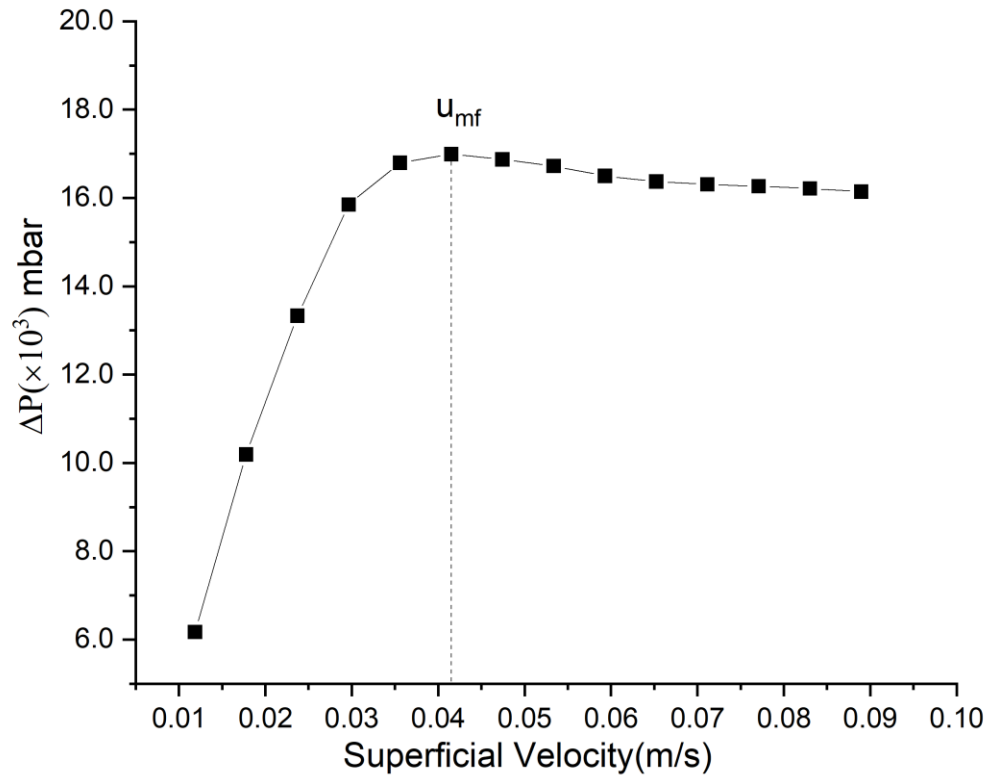


Figure 4.4 Characteristic plot of ΔP against superficial velocity

4.4 Gasification Process and Gas Chromatography

4.4.1 Pressure data

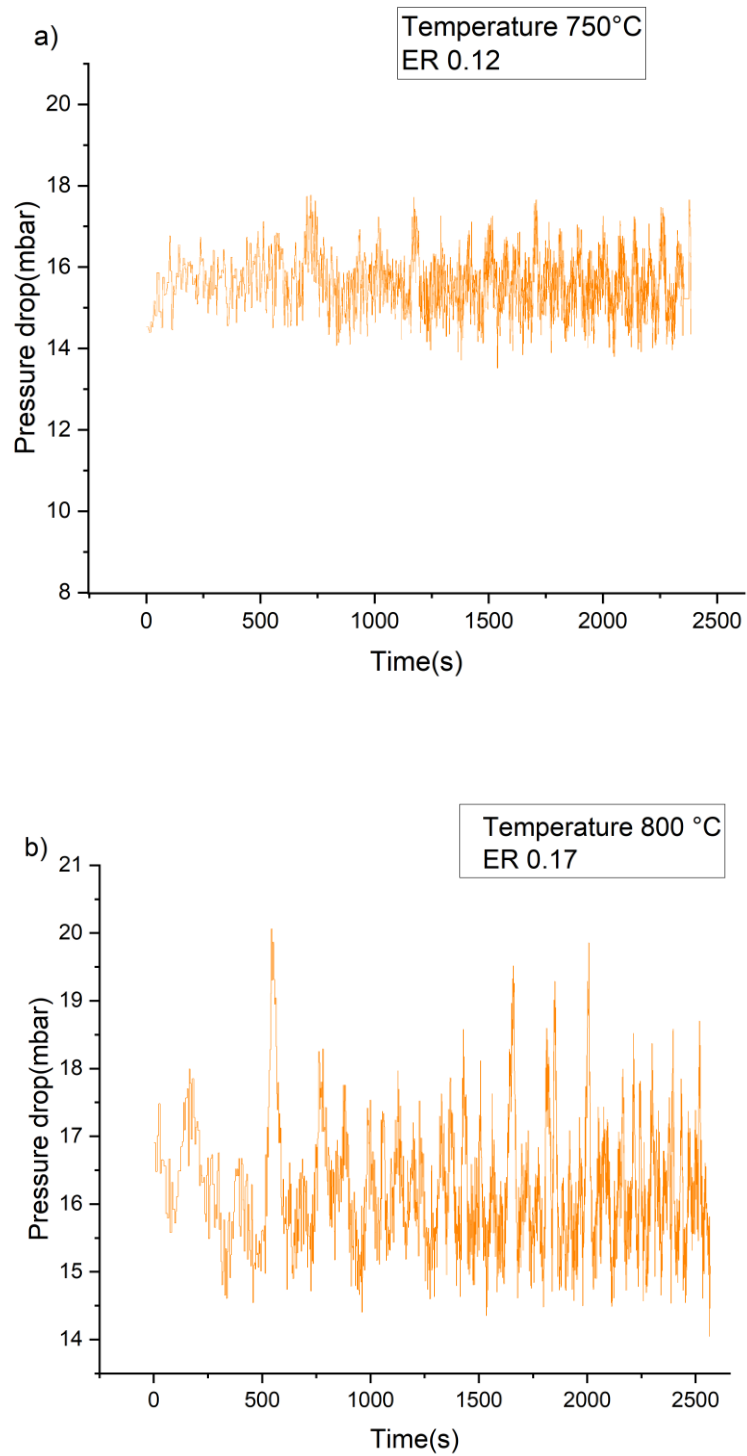


Figure 4.5 The change of bed pressure with time for different ER and temperature

Figure 4.5 illustrates the change of bed pressure with time for different ER and temperature. The gradual increase in bed pressure over time indicates the buildup of unconverted char.

4.4.2 Syngas composition assessment using bed material sand

After the calibration test the screw conveyor was operated at 3% capacity, which resulted in 3.5 kg/h, 5 kg/h and 7 kg/h flow rates for coffee pellets. Since the reactor has a small diameter, altering the biomass feed could result in different fluidization conditions from the altered air flowrate to affect the ER. At 750 °C, CO was produced at 13%,11.48%,11.05% concentration for ER 0.12, 0.17 and 0.24 respectively. The H₂ concentration was 16%,15%,13% for ER 0.12, 0.17 and 0.24 respectively. Similarly, the CH₄ concentration was around 3% for the three equivalence ratio.

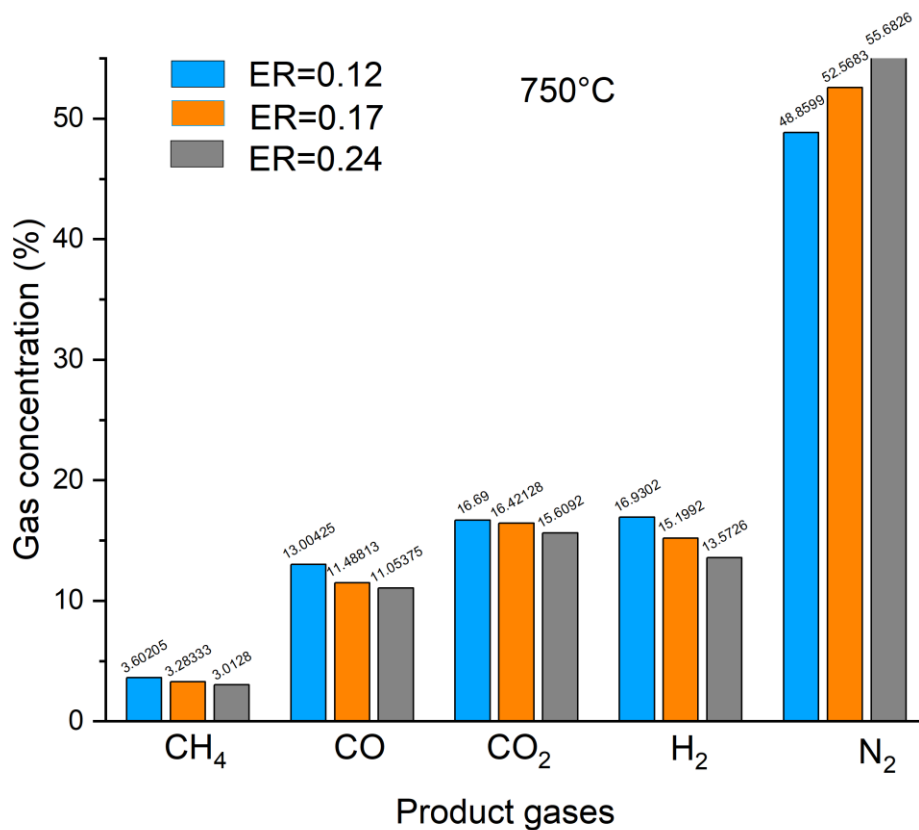


Figure 4.6 Product Gas composition at different ER for sand particles (750°C)

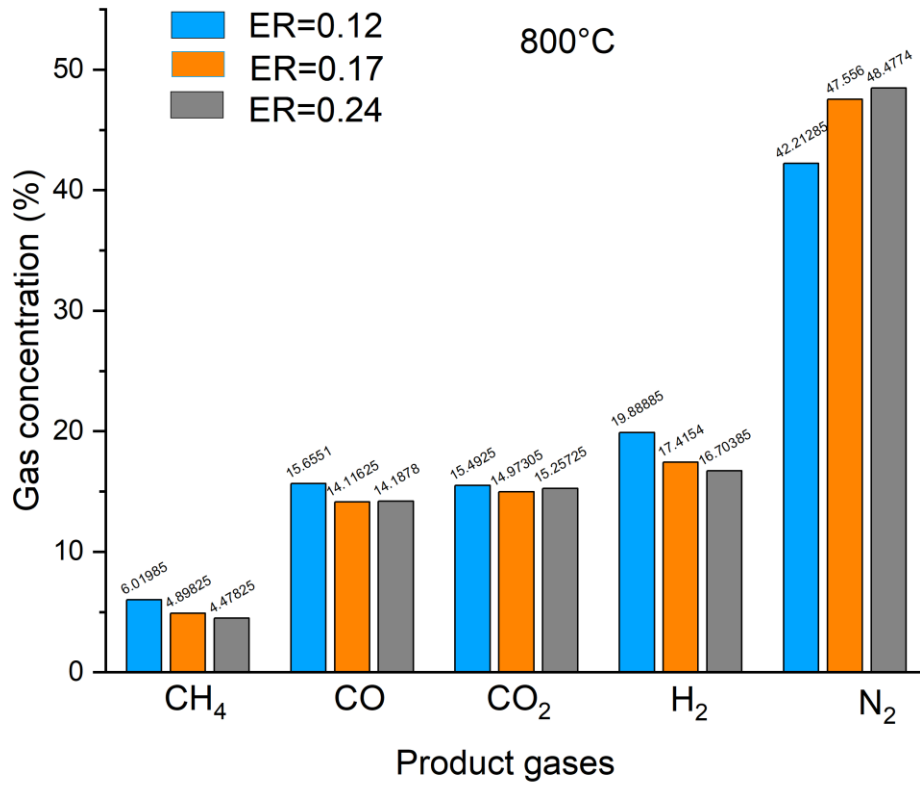


Figure 4.7 Product Gas Composition at different ER for sand particles(800°C)

Adjusting the reactor temperature altered the gas composition. With a higher Equivalence Ratio (ER) increasing air intake and enhancing oxidation reactions, resulting in more CO₂, H₂O, and N₂. At 800°C with an ER of 0.12, methane, carbon monoxide, and hydrogen concentrations rose from 3% to 6%, 13% to 15%, and 16% to 19%, respectively, compared to 700°C. These findings highlight the significant impact of ER and air flow rate adjustments on gas composition, enabling process optimization for desired outcomes.

4.4.3 Syngas composition assessment using bed material olivine

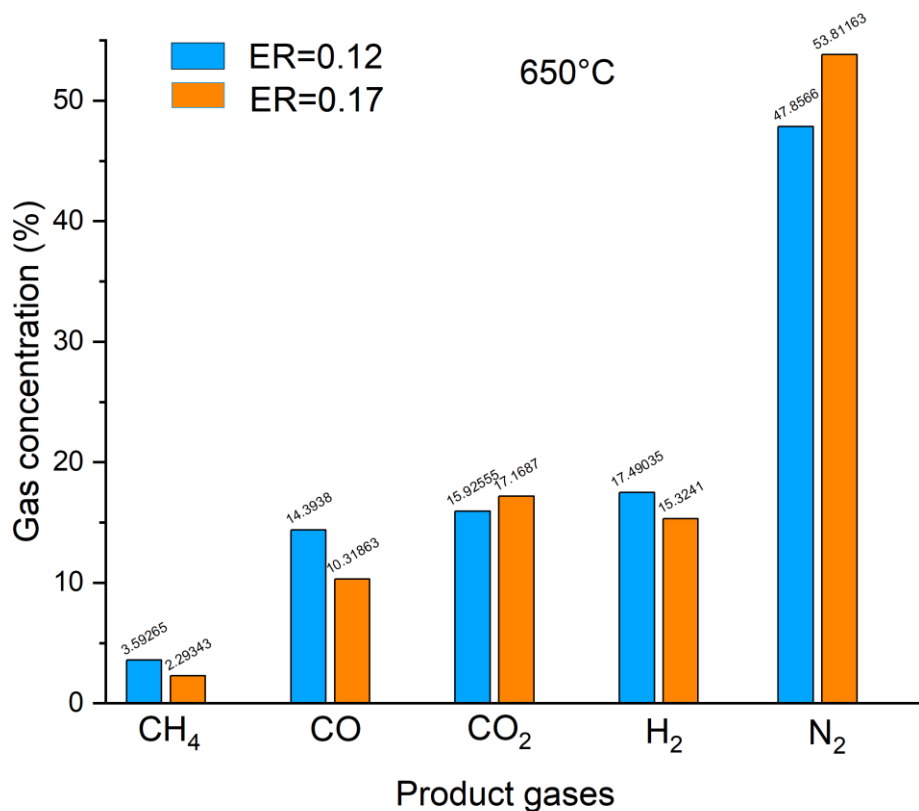


Figure 4.8 Product Gas Composition at different ER for olivine particles(650°C)

The air flow rates of 3.5kg/h and 5kg/hr were introduced to the reactor. A higher ER led to more air being introduced into the gasifier, improving the oxidation reaction and ultimately leading to the creation of more CO₂, H₂O, and N₂. The gas composition was changed as well. Figure 4.8 shows that, the concentration of methane ,carbon monoxide and H₂ decreased from 3% to 2% , 14% to 10% and 17% to 15% respectively. This was because more oxygen was introduced which accelerated the reaction. On the other hand, the composition carbon dioxide increases from 15% to 17% along with increasing equivalence ratio.

4.4.4 Comparison of Syngas composition between sand and olivine as bed material for gasification

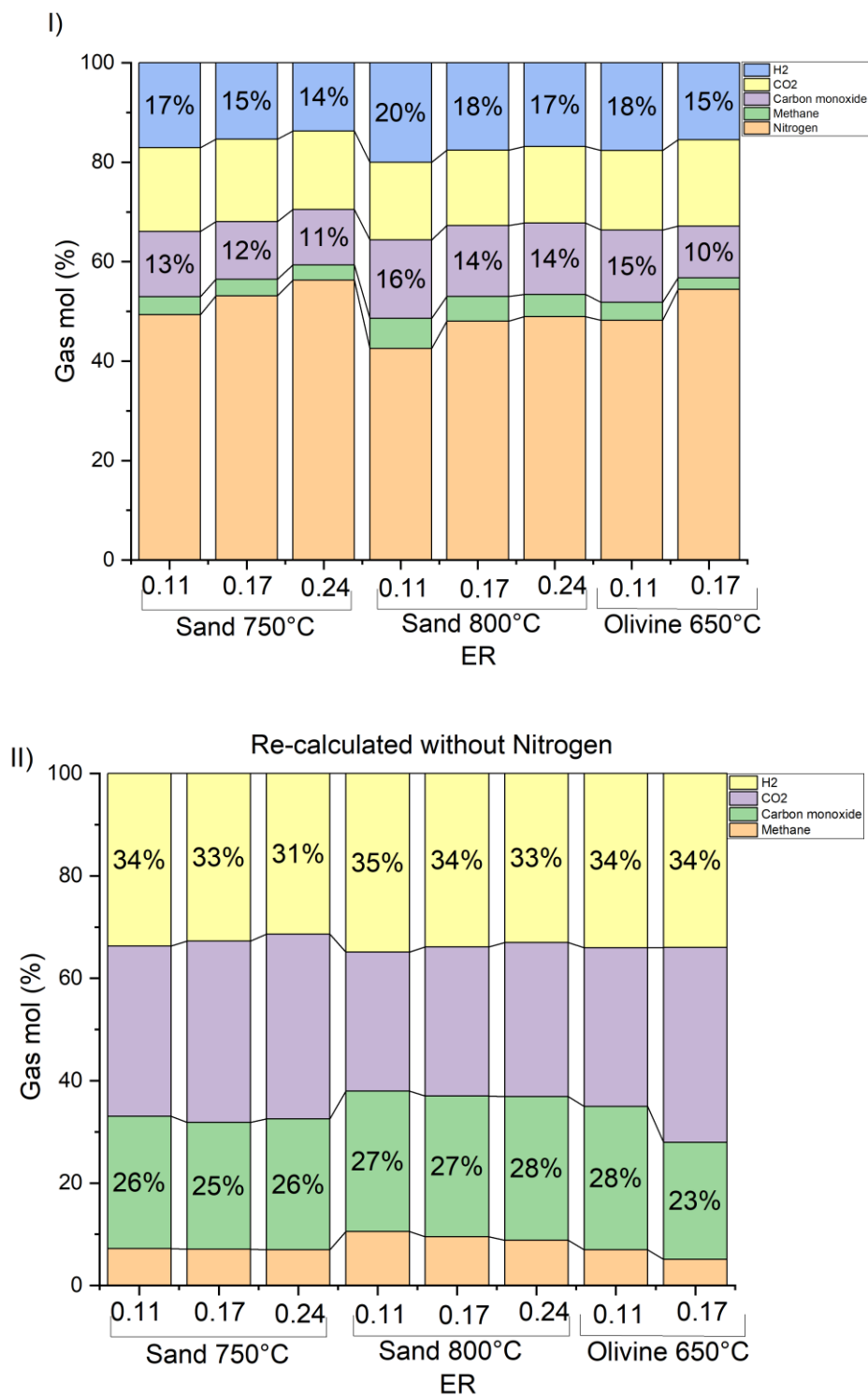


Figure 4.9 Product gas composition of coffee pellets at different equivalence ratio
a)calculated with N₂, b)calculated without N₂

The gas compositions as a function of temperature (included N₂) are plotted in Figure 4.9 I) for different ERs. For sand at 750°C, the gas composition shows a decrease in H₂ from 17% to 14% and CO from 13% to 11% as the ER increases from 0.11 to 0.24. At 800°C, sand reveals a higher H₂ percentage, peaking at 20% for ER 0.11 before stabilizing around 17%, while CO decreases from 16% to 14%. Olivine at 650°C exhibits a reduction in H₂ from 18% to 15% and CO from 15% to 10% as ER increases. These findings suggest that higher temperatures and varying ER values influence the proportions of H₂ and CO₂, while nitrogen remains in the gas mix across all tested conditions and dilutes the gas.

The gas compositions (excluded N₂) are plotted in Figure 4.9 II) . For sand at 750°C, an increase in the Equivalence Ratio (ER) from 0.11 to 0.24 resulted in a decrease in the H₂ concentration from 34% to 31% and the concentration of the CO remained stable. At 800°C, sand maintained a relatively constant H₂ percentage around 34-35%, a slight decrease in CO₂ and a slight increase in CO from 27% to 28%. Olivine at 650°C exhibited a consistent H₂ percentage of 34%, a stable CO proportion around 23%, and almost constant CH₄. These results indicate that higher temperatures stabilize H₂ production, while ER variations primarily affect CO₂ and CO proportions, with methane remaining relatively unaffected across different conditions. The best gas composition was obtained using bed material olivine at temperature 650°C and comparing it with the sand bed materials at temperature 750°C, 800°C gave a significant insight into this data that olivine is expected to enhance syngas composition.

5 Conclusion

The study investigated the behavior of two commonly used bed materials, sand and olivine. It aimed to determine the minimum reactor operating temperature at which a mixture of coffee and sawdust pellets can be gasified to improve the quality of product gas.

To achieve optimal pellets in the pelletization process, it's essential to consider factors such as binders, die size, and pellet drying methods. Moisture levels are particularly critical and vary depending on the type of feed being used. In this study, coffee pellets mixed with sawdust achieved good results with a moisture content of 9%-10%. Proper feed preparation and pellet drying are essential for producing quality pellets. Therefore, successful pellet production depends on balancing these factors and having a thorough understanding of machine operation.

A significant effect of temperature and equivalence ratio on the gas composition was observed. Various equivalence ratios (0.12, 0.17, and 0.24) were experimented, showing that, product gas quality seems to decline with an increase in the equivalence ratio at a specific temperature as a result of N₂ dilution. For bed material sand, The percentage of carbon monoxide and of hydrogen has been shown to decrease (13% to 11%, and 16.9% to 13.5% respectively) in the syngas when the ER was increased from 0.11 to 0.24 at 750°C temperature. The respective CO and H₂ concentration were decreased from 15.6% to 14% and 19.8% to 16.7% for coffee pellets at 800°C temperature. The respective ERs were 0.12 and 0.24. However, when the gas concentration was calculated on a nitrogen free basis, it seemed to be more stable along with the changing ER value (33% -35% H₂, 26-28% CO)

For olivine with ER 0.11 and at 650°C, a better syngas quality is reflected in the higher CO concentration(14%) of the product gas when compared to using sand and performing gasification at higher temperatures. Additionally, even at lower gasifier temperature of 650°C, using olivine leads to a product gas quality with hydrogen concentration(17%) similar to gasifier operated with sand at higher temperatures (16.9%,19%) and this was observed at all the ER values tested. Thus, the experiments suggest that olivine is expected to performs better than sand at any given temperature. The quality of the product gas seems to be influenced by the mixing behavior of the bed particles and the supplied fuel. Choosing the right airflow rate based on bed particle size is crucial for achieving optimal mixing.

6 References

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Appendices

Appendix A

Particle mean diameter and PSD:

a)

Sieve range (um)	d, mean size (um)	Initial weight (g)	Final weight (g)	Particle weight (g)	w, weight fraction	w/d
200	355	277.500	344.96	697.65	352.69	0.352704108 0.001271
355	425	390.000	463.51	736.18	272.67	0.272680907 0.000699
425	500	462.500	416.17	645.23	229.06	0.229069163 0.000495
500	600	550.000	300.35	445.07	144.72	0.144725789 0.000263
600	650	625.000	292.82	293.64	0.82	0.000820033 1.31E-06
ToTAL					999.96	1 0.00273
		mean particle size (um)	366.3108141			

b)

Sieve range (um)	d, mean size (um)	Initial weight (g)	Final weight (g)	Particle weight (g)	w, weight fraction	w/d
200	250	225	344.7	421.46	76.76	0.0926 0.00041
250	355	302.5	354.67	512.83	158.16	0.1908 0.00063
355	425	390	464.2	773.18	308.98	0.3727 0.00096
425	500	462.5	416.85	669.18	252.33	0.3044 0.00066
500	600	550	300.91	333.56	32.65	0.0394 0.00007
600	650	625	292.87	293.06	0.19	0.0002 0.00000
ToTAL					829.07	1.0000 0.00273
		mean particle size (um)	366.601658			

c)

Sieve range (um)	d, mean size (um)	Initial weight (g)	Final weight (g)	Particle weight (g)	w, weight fraction	w/d		Reading1	366.3108
200	355	277.5	344.96	510.76	165.8	0.211	0.00076	Reading2	384.1553
355	425	390	464.76	775.6	310.84	0.395	0.00101	Reading3	366.6017
425	500	462.5	416.81	677.34	260.53	0.331	0.00072	Mean	372.3559
500	600	550	266.44	315.62	49.18	0.063	0.00011	Standard deviation	10.2196
600	650	625	292.86	293.13	0.27	0.000	0.00000		
Total					786.62	1.000	0.00260		
		mean particle size (um)	384.1553085						

$$\text{Particle mean diameter} = \frac{\sum w}{\sum \frac{w}{d}}$$

Appendix B

Cold bed experiment

			Superficial velocity m/s		
Volume flow rate(L/min)	m ³ /s	Area			ΔP
4	6.66667E-05	0.005621	0.01186		6445.257
6	0.0001	0.005621	0.01779		9553.302
8	0.000133	0.005621	0.02372		13615.35
10	0.000167	0.005621	0.029649		15849.44
12	0.0002	0.005621	0.035579		16790.64
14	0.000233	0.005621	0.041509		16964.97
16	0.000267	0.005621	0.047439		16866.95
18	0.0003	0.005621	0.053369		16689.32
20	0.000333	0.005621	0.059299		16575.58
22	0.000367	0.005621	0.065229		16262.53
24	0.0004	0.005621	0.071159		16373.3
26	0.000433	0.005621	0.077089		16276.22
28	0.000467	0.005621	0.083019		16118.98
30	0.0005	0.005621	0.088948		16189.23

Appendix C

Method used for calculating pellet density

For the density calculation,

$$\text{Density}(\rho) = \frac{\text{mass}(m)}{\text{volume}(V)}$$

Water displacement method was used to calculate the volume of pellets and procedure is as follows:

- Measured the weight of pellets in a weighing machine.
- Took small cylindrical jars that measured up to 10 ml.
- Filled water up to 5ml in that jar.
- Dropped pellet in that cylindrical jar and then read the water level in that jar, as when pellets are dropped in that jar water level increased due to the displacement of water by pellet.
- The density of pellet was calculated by dividing mass by displaced volume, converting all units into standard units



Appendix D

Unconverted Carbon measurement

Ultimate and Proximate analysis of coffee pellets

Components	Coffee pellets
Ultimate analysis (dry basis.,wt %)	
H2	6.9
C	53.9
O2	36.98
N2	2.22
Proximate analysis (dry basis.,wt %)	
Moisture	10.3
Ash	2.2
Volatiles	73.3
Fixed carbon	14.2
Heating value, (MJ/kg)	10.503

	Experiments with sand			
Air flow rate :	3.5 kg/h	5 kg/h	7kg/h	
% N2:	48.86	52.57	55.68	%
Total gas flow	0.19619826	0.26050292	0.34433359	kmol/h
Components:				
H2	16.93	15.2	13.57	mol%
O2	0.9136	1.039775	1.06905	mol%
CO	13	11.49	11.09	mol%
CH4	3.6	3.28	3.01	mol%
CO2	16.69	16.42	15.61	mol%
N2	48.86	52.57	55.68	mol%
Components:				
H2	0.03321637	0.03959644	0.04672607	kmol/h
O2	0.00179247	0.00270864	0.0036811	kmol/h
CO	0.02550577	0.02993179	0.03818659	kmol/h
CH4	0.00706314	0.0085445	0.01036444	kmol/h
CO2	0.03274549	0.04277458	0.05375047	kmol/h
N2				
Carbon balance:				
C in:	0.16357842	0.16357842	0.16357842	kmol/h
C out:	0.0653144	0.08125086	0.10230151	kmol/h
C-conversion	39.9284963	49.6708945	62.539736	%
Unconverted	60.0715037	50.3291055	37.460264	%
Unconverted	0.09826401	0.08232755	0.06127691	kmol/h
Unconverted	1.17916816	0.98793064	0.73532287	kg/h

Experiments with olivine			
Air flow rate :	3.5 kg/h	5 kg/h	
mol % N2:	47.86	53.81	%
Total gas flow rate out of the gas	0.200	0.254	kmol/h
Components:			
H2	17.49	15.32	mol%
O2	1.0835	0.74105	mol%
CO	14.39	10.32	mol%
CH4	3.59	2.29	mol%
CO2	15.93	17.17	mol%
N2	47.86	53.81	mol%
H2	0.0350	0.0390	kmol/h
O2	0.0022	0.0019	kmol/h
CO	0.0288	0.0263	kmol/h
CH4	0.0072	0.0058	kmol/h
CO2	0.0319	0.0437	kmol/h
N2			
Carbon balance			
C in	0.1636	0.1636	kmol/h
C out	0.0679	0.0758	kmol/h
C-conversion	41.5	46.3	%
Unconverted carbon:	58.5	53.7	%
Unconverted Carbon kmol/h:	0.0957	0.0878	kmol/h
Unconverted Carbon kg/h:	1.1479	1.0535	kg/h

Appendix E

Composition of olivine

Components(%)		Olivine
MgO	Magnesium Oxide	46.5
SiO*	Silicon Oxide	41.5
Fe ₂ O ₃	Iron Oxide	6.8
Al ₂ O ₃	Aluminium Oxide	0.75
Cr ₂ O ₃	Chromium Oxide	0.44
NiO	Nickel Oxide	0.30
MnO	Mangan Oxide	0.08
L.O.I.**	Loss on Ignition**	4.0

Appendix F

Task Description

FMH606 Master's Thesis

Title: Syngas production from air gasification of waste feedstock with natural catalyst, Olivine, as the bed material

USN supervisor: Prof. Britt Margrethe Emilie Moldestad
PhD Rajan Jaiswal

SUST supervisor: Prof. Salatul Islam Mozumber

Background:

In pursuit of the global carbon-neutral objective, an urgent transition from non-renewable fossil fuels to alternative energy sources is necessary. Utilizing waste feedstock for energy production can be an alternative option that can address two major global challenges: waste management problem and supply of clean energy demand. Among the thermochemical conversion routes, gasification technology is widely used to convert solid wastes into gaseous products. The product gases from the gasification are rich in hydrogen and carbon monoxide that can be utilized for several applications, including the production of valuable chemicals, heat, or power generation. Among the various gasification reactors, bubbling fluidized bed reactor (BFBR) has gain attraction for energy conversion since the BFBR provides flexibility to use a wide variety of feedstocks, is scalable, simple in design, and provides better heat and mass transfer during the conversion process.

In a BFB gasifier, the hot particle bed is set into motion by passing the fluidizing gas such as air, or steam. The hotbed particles provide the necessary heat for the thermal degradation of the carbonaceous solid in an oxidant deficit environment. Efficient heat transfer at higher reactor temperature is desirable for better conversion efficiency. However, challenges arise when operating the temperature at high temperatures, particularly with waste feedstocks containing a high ash content, leading to issues such as agglomeration and bed defluidization.

Alternatively, catalyst can be used to gasify the waste feedstock at a lower reactor operating temperature and obtain higher-quality product gas. This work will employ a natural catalyst, Olivine particles, as bed material and assess the syngas production potential of the waste pellets. The waste pellets consist of mixture of coffee grounds and sawdust. This project will aim to find a minimum reactor operating temperature that gives a higher yield of H₂ and CO in the product gas using Olivine particle as the bed material.

The waste feedstock pelletization process will be executed utilizing a laboratory-scale pelletizer housed at USN. Similarly, gasification experiments will be conducted using a 20 kW bubbling fluidized bed (BFB) gasifier located at USN. Gasifier performance under varying operating conditions will be assessed based on the carbon conversion and gasification efficiency. The product gas composition at different operating conditions will be analyzed through offline gas chromatography (GC).

Objective:

The primary objective of this project is to find the minimum reactor operating temperature at which the mixture of coffee and sawdust pellets can be gasified with higher product gas quality using olivine particles. To accomplish the objective the following tasks will be carried out:

Task descriptions

1. Feedstock preparation and pelletization of the coffee grounds and sawdust mixture.
2. Preparation and sieving of the bed material sand and olivine particles.
3. Fluidization tests on the cold flow model to identify the flow dynamics behaviour of the bed with the olivine and sand particles.
4. Calibrate pellets feed rate via screw conveyors.
5. Gasification experiments with sand and olivine particles at different air-to-fuel ratio
6. Measure pressure, temperature and monitor reactor operating conditions throughout the operation.
7. Analysis of the collected samples in an offline GC chromatography.
8. Measure the amount of unconverted carbon at the end of each gasification test.

Supervision:

As a general rule, the student is entitled to 15-20 hours of supervision. This includes necessary time for the supervisor to prepare for supervision meetings (reading material to be discussed, etc).

Signatures:

Supervisor (date and signature): 01.03.2024



Student (write clearly in all capitalized letters): NUJHAT MUBARRAT

Student (date and signature): Nujhat; 01.03.24