1 Introduction

Based on the Wobbe Index[1], fuel gases can be categorized into hydrogen-rich gas, methane-rich gas (natural gas, synthetic natural gas (SNG) and their substitutes, e.g. biogas) and liquefied petroleum gas (LPG) [1]. Widely used in many applications, e.g. cooking, heating, generating electricity, as transportation fuels and as feedstock for the manufacture of chemical products, fuel gases play an important role in the global energy structure. The key world energy statistics from International Energy Agency (IEA) [2] shows that, in 2014, natural gas solely made up 21.2 % of the world total primary energy supply (Figure 1-1).

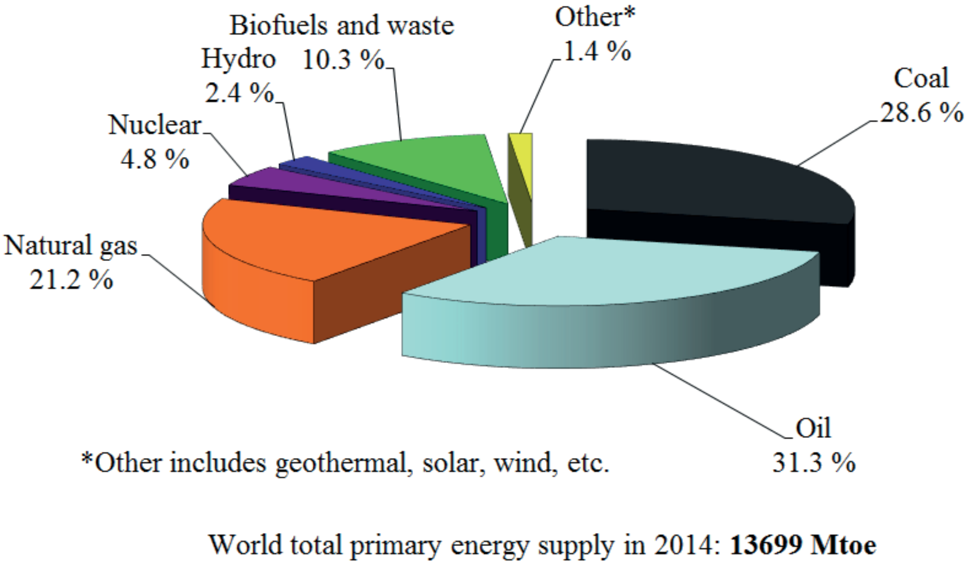

Figure 1-1: World primary energy supply by fuel type in 2014 (data from [2]).

Currently fuel gases are produced dominantly from non-renewable fossil fuel resources, i.e. coal, natural gas and petroleum, which have limited reserves and will be eventually depleted. In addition, the increasing greenhouse gas (GHG) emissions, principally from fossil fuel use, is leading to a rapid climate change, which will likely result in reduced diversity of ecosystems and the extinction of many species [3]. Aiming to reduce GHG emissions and the dependency on fossil fuels, renewable and environmental friendly energy sources, i.e., wind, solar, hydropower, biomass, geothermal and ocean energy, are being actively utilized. Among these sources, biomass is the only non-fossil carbon

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[1] Wobbe index is a characteristic value for the interchangeability of gases with regard to the heat input to gas appliances. It is the heating value divided by the square root of the specific gravity.

source and the fourth largest primary energy source after oil, coal and natural gas. In addition, it is storable and its production is predictable. Through thermo-chemical or biochemical/biological conversion processes, this renewable feedstock can be converted to hydrogen-rich or methane-rich fuel gas in a more sustainable way. As such, it holds a great potential to replace fossil fuels for fuel gas production.

By definition, biomass refers to “the biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste” [4]. According to this definition, biomass resources include a wide range of materials, e.g. wood chips, straw, miscanthus, poultry waste, sewage sludge, etc., which have diverse physical and chemical properties. The main properties that influence the selection of conversion process are moisture content, calorific value, proportions of fixed carbon and volatiles, ash content, alkali metal content and the ratio of cellulose to lignin [5]. Biomass with high moisture content and cellulose/lignin ratio is most suitable for biochemical/biological conversion process.

Three conversion processes, namely anaerobic digestion, pyrolysis and gasification, can be employed to produce fuel gas from biomass:

- anaerobic digestion (biochemical/biological) is the conversion of biomass to primarily methane (CH_4) and carbon dioxide (CO_2) by micro-organisms in the absence of oxygen. Depending on the bacteria species (psychrophilic, mesophilic or thermophilic), the operating temperature is typically between 10 °C – 60 °C. The thermophilic mode of operation results in a higher biogas yield [6],
- pyrolysis (thermo-chemical) is the thermal decomposition (typically above 300 °C) of biomass in the absence of oxygen. The major products are char, bio-oil and gases mainly containing CH_4, CO_2, carbon monoxide (CO) and hydrogen (H_2). The gas yield is generally maximized at high heating rates, high temperatures and short residence times [7], and
- gasification (thermo-chemical) also occurs at high temperatures (typically above 650 °C), at atmospheric or high pressures, and in the presence of gasification agents, e.g. air, oxygen, steam, CO_2 or a combination of them. During gasification process, biomass goes through a number of reactions (drying, devolatilization, oxidation and reduction) in series or simultaneously and is transformed into fuel gas, which consists of CO, H_2, CH_4, steam, CO_2, light hydrocarbons and, in case of air gasification,

nitrogen (N_2). Depending on the fuel type and the gasification technology, the fuel gas may contain a certain amount of impurities, e.g. tar, particulate matters, H_2S or hydrogen chloride (HCl).

General characteristics of anaerobic digestion, pyrolysis and gasification are contrasted in the following Table 1-1.

Table 1-1: General comparison of processes for fuel gas production from biomass.

Process	**Biochemical/biological**	**Thermo-chemical**	
	anaerobic digestion	**pyrolysis**	**gasification**
Conditions	biological decomposition, atmospheric pressure, low temperature	thermal decomposition, atmospheric or high pressure, high temperature	
Products	gases, digestate	char, bio-oil, gases	gases
Solid retention time	3 – 62 days[6]	a few seconds or minutes	
Biomass preparation	watering, grinding	drying, grinding or pelleting	
Gas yield [Nm^3/kg biomass, dry]	0.1 – 1.6[6]	0.1 – 0.55[8]	0.86 – 2.45[9]
Distribution of main fuel gas components [Vol. %]	CH_4: 55 – 70[6]	CH_4: 9 – 17[8] H_2: 1 – 25[8] CO: 31 – 53[8]	CH_4: 2 – 12[9] H_2: 5 – 56[9] CO: 10 – 52[9]

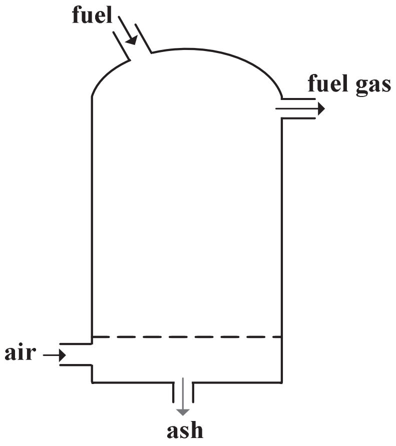
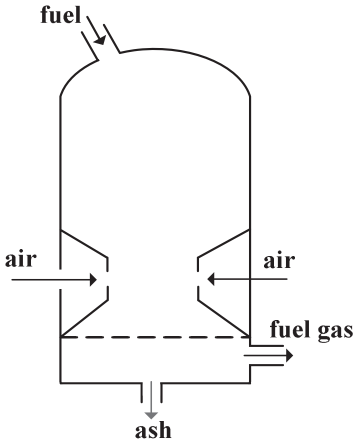
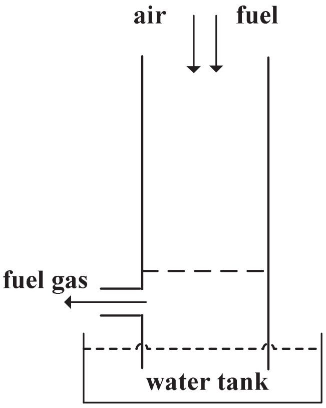
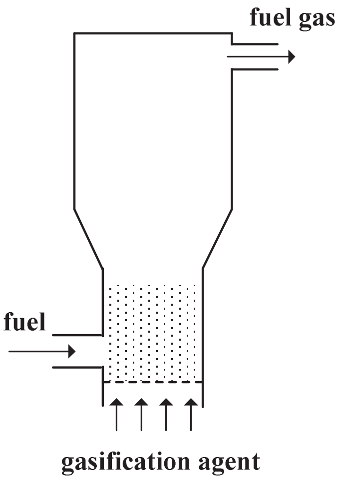
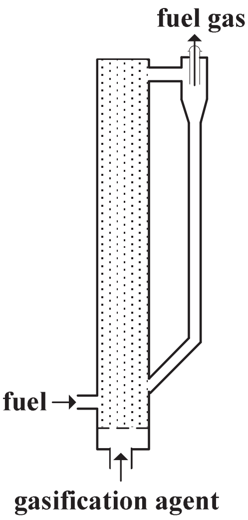
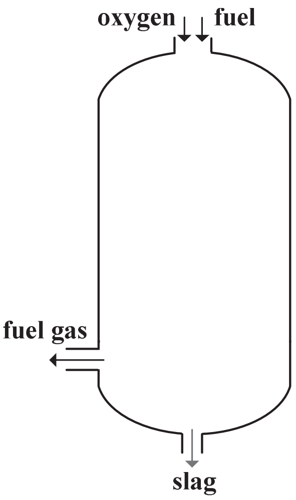
As shown in Table 1-1, biomass gasification has a higher gas yield compared to anaerobic digestion and pyrolysis. In addition, the product gas, after proper gas treatment, has a variety of applications. It can be used in gas engines or fuel cells to produce heat and electricity. By the adjustment of gasification conditions or by downstream reforming processes, the H_2/CO ratio of product gas can also be varied accordingly and used for the production of chemicals/fuels, e.g. ammonia, synthetic natural gas (SNG), or methanol. Therefore, biomass gasification technology has gained significance in the field of renewable energy and has undergone rapid development over the last decades. In the following chapter, this technology is briefly described.

1.1 Biomass Gasification Technology

Gasification technology was already commercialized in the 1800s to produce “town gas” from coal/wood for heating and lighting [10]. Due to the discovery of oil in the 1860s and the construction of natural gas pipelines starting in the late 19th century, the need for coal/wood gasification was gradually reduced. Major process development at this time includes the Winkler fluid-bed process in 1922, the Lurgi pressurized moving-bed process in 1931 and the Koppers-Totzek entrained-flow process in the 1940s [10]. Based on these developments, gasifiers nowadays can still be classified into three categories that modern designs generally fall into: fixed-bed gasifiers, fluidized-bed gasifiers and entrained-flow gasifiers.

In fixed-bed gasifiers, bulky fuels are added to the top of the gasification chamber and slowly move down through gravity, during which the solid fuels react with the gasification agent and are converted into gaseous products. Ash migrates to the bottom, where it can be removed. Depending on the movement of gases relative to the fuel bed, fixed-bed gasifiers can be typically classified as up-draft, down-draft, cross-draft and open-core gasifiers, among which the cross-draft gasifiers are especially developed for charcoal gasification [11]. In fluidized-bed gasifiers, bed materials such as sand particles are suspended in the upward flow of gasification agents and behave like boiling fluid. Fuel particles are normally directly introduced to the hot fluidized bed, where they get intensively mixed with bed materials and react with gasification agents. Depending on the flow patterns of solid particles, fluidized bed gasifiers can be categorized into bubbling fluidized bed (BFB) and circulating fluidized bed (CFB) gasifiers. The gas velocities in BFBs are relatively low and therefore the majority of bed materials remain in the fluidized bed. On the other side, the gas velocities in CFBs are high enough to entrain the bed materials out of the reactor. After cyclonic separation, bed materials flow back to the reactor and start the next circle. In entrained-flow gasifiers, finely-ground fuel particles are injected in a co-current flow with the gasification agent (mostly oxygen) into the reactor. The solid residence time is very short because of the high injection velocity. Therefore, a high operating temperature (mostly > 1000 °C) is required to ensure a good conversion process. This temperature is well above the ash melting temperature. As a result, ash is removed as molten slag from the reactor bottom. The aforementioned gasifier types are schematically illustrated in Table 1-2.

Table 1-2: Different gasifier types.

Up-draft fixed-bed	**Down-draft fixed-bed**	**Open-core fixed bed**
		
Bubbling fluidized bed	**Circulating fluidized bed**	**Entrained flow bed**
		

Mainly due to their simple and robust construction, the fixed-bed type of gasifiers has many practical applications for heat and electricity production from biomass that cover a wide power range. A few examples are listed as follows. Spanner Re² GmbH produces down-draft gasifier systems, which generate electric power between 30 and 45 kW_{el}. Only wood chips having specified particle sizes, moisture contents and fine particle contents can be used in their systems [12]. Babcock & Wilcox Vølund A/S built a 3.5 MW_{th} updraft gasifier for the municipality of Harboøre (Denmark) in December of 1993, which operated between 1996 and 2011 with more than 8,000 annual operating hours. Again only wood chips are used as fuels [13]. Nexterra Systems Corp. also adopts the updraft gasifier technology and provides systems with output from 2 to 40 MW_{th} and 2 to 15 MW_{el}. Mainly woody residues, e.g. urban wood waste, sawmill waste or clean construction debris are used as fuels in their systems [14]. Modification on fixed-bed gasifier has been made by different developers to improve the product gas quality. As an example, XYLOWATT (Belgium) develops the NOTAR® gasifier system, in which the devolatilization, combustion (oxidation) and reduction of feedstock are separated in three different zones. The combustion takes place exclusively in the gaseous phase (combustion of pyrolysis gas with air). It is said that nearly 99.95 % of tar in the product gas is removed and the formation of clinker is also prevented. Mainly woody wastes are used in this system [15].

The entrained flow gasifier system seldom finds its application for biomass fuels in practice because of the strict requirement on fuel particle size and the high energy input necessary for maintaining a high temperature in the reactor. Cortus AB (Sweden) develops the WoodRoll® technology, in which the biomass drying, pyrolysis and gasification are physically separated in three sequent steps. In the final step, the biomass char produced in the pyrolysis step will react with steam in an entrained flow gasifier to produce synthesis gas [16].

In terms of both fuel flexibility and operational variability, fluidized bed systems have certain advantages over the aforementioned gasifier systems. The circulating fluidized bed (CFB) system is already widely used in coal-fired power plants and is more suitable for applications in the higher power range (typically more than 10 MW_{th}). Amec Foster Wheeler and Metso provide biomass fueled CFB gasification systems. Reference projects are, for example, the Lahti gasification unit (Finland) with a capacity between 45 MW_{th} and 70 MW_{th} fueled by sawdust, wood chips, wood wastes and refuse-derived fuels (RDF) [17] and the Värö gasification unit of 35 MW_{th} in Sweden fueled with by-products from pulp production [18]. It has to be mentioned that biomass gasification units in this upper power range require a substantial quantity of feedstock from the local area or from area nearby with small transport radius. However, this is not always the case. Biomass resources are mostly scattered and, in case of agricultural and forestry residues, have seasonal variations. For decentralized units in the lower power range (1-10 MW_{th}), BFB systems are preferred to CFB systems primarily because of their lower capital costs and higher adaptability to fuel types and properties, especially the fuel particle sizes. Nevertheless, commercial bubbling fluidized bed (BFB) biomass gasification units combining gas engines or turbines for decentralized combined heat and power (CHP) generation are scarce. Furthermore, integrated systems of BFB biomass gasification with fuel cells or with the production of other chemicals or synthetic fuels are still in the research stage. One of the technical obstacles is the unknown gasification behavior of different biomass fuels in BFB reactors and the resulting fuel gas compositions, especially the concentrations of H_2 and CO. This is however important for the gasifier design, its operation and the design of downstream equipment. In a joint project “ProBio” between Fraunhofer Society and Max Planck Society with the aim of developing an integrated BFB biomass gasification and fuel cell system, the business unit of process and plant engineering (PAT) at the Fraunhofer Institute for Factory Operation and Automation IFF in Magdeburg dedicated its research effort on the theoretical and experimental investigation of biomass gasification in BFB reactors in preparation for an optimal interconnection between components of the integrated system. This investigation has given an incentive to this dissertation.

1.2 Objectives and Outline of the Present Work

The aim of this dissertation is to have an enhanced understanding of fuel gas production from gasification of various types (woody and non-woody) of biomass and waste using atmospheric BFB gasifiers. A systematic methodology combining both theoretical and practical approaches is adopted to achieve this aim, which includes literature review, performing gasification experiments with different types of biomass fuels using a laboratory-scale bubbling fluidized bed (BFB) reactor, development of a design methodology for BFB biomass gasifiers and a kinetic model for the prediction of fuel gas concentrations, especially the concentrations of H_2 and CO, which can be used for the optimization of biomass gasification process in BFB reactors.

To start with, a literature review is conducted to understand the influence of different operating parameters on fuel gas characteristics, gasification efficiencies as well as process stability and to collect recommended values of these parameters for the reactor design and the experimental planning (section 2.1). As the second part of this review (section 2.2), different types of models for biomass gasification in BFB systems, i.e. equilibrium, kinetic, computational fluid dynamics (CFD) and artificial neural network (ANN) models, are compared in terms of their complexity and predictability. Based on the comparison, the kinetic approach is adopted in this study for the modeling of atmospheric BFB gasifiers.

A step-by-step design methodology for BFB gasifiers is developed and explained in section 3.1. This methodology is supported by the two-phase theory of fluidization and a set of empirical equations that describe the BFB fluid dynamics. The selected reaction kinetics, the mass and energy balance as well as the algorithm for the kinetic model are discussed in detail in section 3.2.

Major operating parameters are tested systematically using a laboratory-scale bubbling fluidized bed (BFB) gasifier. The experimental set-up, the materials (fuels and bed materials) used, the experimental plan and the operating procedure are described in Chapter 4. Experimental results are evaluated and the influence of operating parameters on fuel gas characteristics, gasification efficiencies and process stability is demonstrated in Chapter 5.

In Chapter 6, the kinetic model is not only validated with this author's experimental data but also with quoted values from BFB gasifiers of larger scales (pilot- and demonstration-scales). The design methodology and the kinetic model are then integrated in a Microsoft EXCEL® tool. The use of this tool is demonstrated in Chapter 7 by designing a demonstration-scale atmospheric BFB for air gasification of rice husks. In the end, conclusions regarding the design procedure, the experimental findings and the kinetic model are given in Chapter 8.

2 Review of Biomass Gasification in Bubbling Fluidized Bed Systems

Fuel gas characteristics, gasification efficiencies and process stability are determined by a number of operating parameters, such as fuel properties, temperature, bed materials and gasification agents. Section 2.1 is devoted to the understanding of how these parameters influence the bubbling fluidized bed (BFB) biomass gasification process. To facilitate the model development in section 3.2, current available simulation models for biomass gasification in BFB systems have been reviewed and summarized in section 2.2.

2.1 Operating Parameters

A considerable amount of literature has been published on the experimental study of biomass gasification using BFB gasifiers. The review of papers/theses published since 1981 indicates that the major operating parameters include temperature, gasification agent type, fuel properties and bed material type. Other parameters such as bed height, superficial gas velocity, gas residence time, throughput, weight hourly space velocity (WHSV), the location of the fuel feeding point and the secondary air or steam injection are occasionally investigated. Most of the experiments were conducted with laboratory-scale (1 kW – 10 kW) or technical-scale (10 kW – 50 kW) facilities, while only a few were carried out using pilot-scale (50 kW – 200 kW) or demonstration-scale (200 kW – 1000 kW) atmospheric BFB gasifiers. The influence of the aforementioned operating parameters on the fuel gas characteristics (gas composition, yield, lower heating value (LHV) and tar content), the gasification efficiencies (cold gas efficiency (CGE), carbon conversion efficiency (CCE) and steam conversion efficiency (SCE)) and the process stability were investigated.

2.1.1 Temperature

Temperature is shown to be one of the most important operating parameters in the biomass gasification process and has a strong influence on the fuel gas characteristics, gasification efficiencies and process stability. The temperature range found in the literature is between 650 °C and 950 °C.

It has been experimentally proven that the fuel gas yield increases with operating temperature [19-34] because of the greater gas production from the initial pyrolysis step, the enhanced endothermic reactions of char gasification as well as the tar reforming and cracking reactions at elevated temperatures [25, 26, 31, 35-40]. As a result, the tar content in the fuel gas decreases with increasing temperature [24-26, 28, 29, 32, 39, 41-43].

The major combustible components of fuel gas, i.e. H_2, CO and CH_4, show different tendencies with increasing temperature. The H_2 concentration increases with temperature [19-23, 27, 28, 31, 36, 37, 41, 43-46] because high temperature is favorable to hydrogen production through endothermic reactions such as water-gas, steam or dry reforming of tar as well as tar cracking [28, 44, 47]. Hoque et al. [34] conducted air gasification experiments with coconut shell using a technical-scale (21 kW_{th}) bubbling fluidized bed (BFB) gasifier at different temperatures (627 °C – 842 °C) and described H_2 concentration as a linear function of temperature. Unlike H_2 concentration, three different trends regarding the change of CO concentration with increasing temperature have been observed:

- The CO concentration decreases steadily with increasing temperature [22, 27, 28, 31, 46]. Lv et al. [22] conducted air-steam gasification experiments with pine sawdust at temperature between 700 °C and 900 °C using a laboratory-scale BFB gasifier. They concluded that the concentration of CO was mainly determined by the exothermic Boudouard reaction, which was not favorable at high temperature. In addition, the rate of the forward water-gas-shift (WGS) reaction increases with temperature before reaching equilibrium, whereby more CO is consumed [28, 46].
- The CO concentration increases with temperature [21, 23, 36, 37, 41, 43, 48]. The main cause of such an increase was believed to be the enhanced water-gas reaction and the reforming reactions of methane and tar at high temperatures [48, 49].
- The CO concentration is fairly constant over the range of temperature. This conclusion was derived from air-steam gasification experiments with sawdust at temperatures between 750 °C and 950 °C using a laboratory-scale BFB gasifier by Turn et al. [44].

The following Figure 2-1 demonstrates the different trends of CO concentration as a function of the temperature.

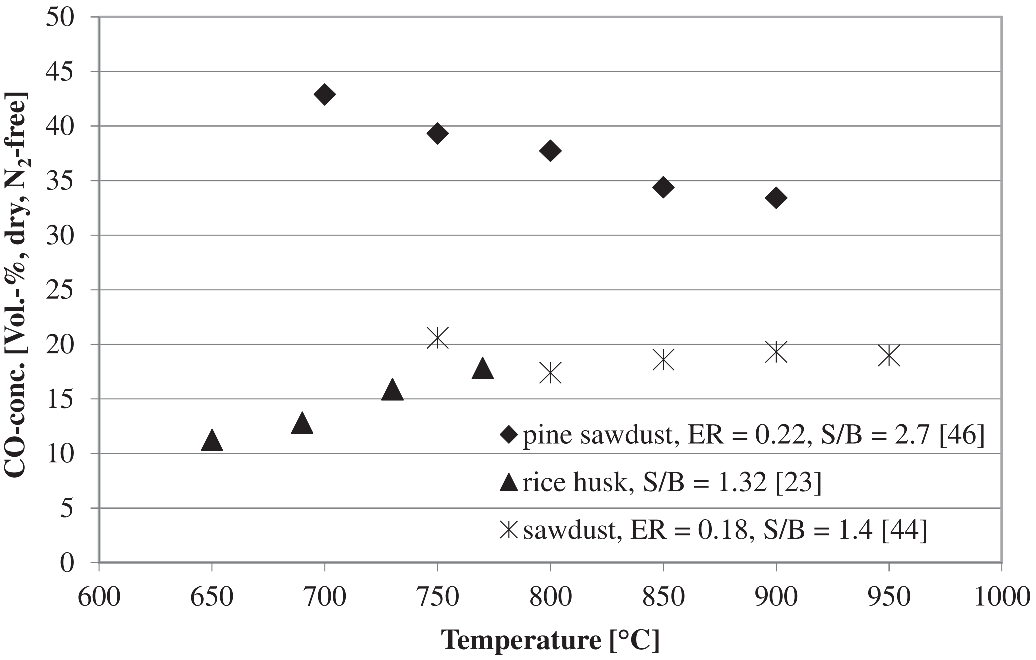


Figure 2-1: CO-concentration as a function of temperature.

Similarly, the concentrations of CH_4 and other light hydrocarbons (C_2H_2, C_2H_4 and C_2H_6) have been observed to change in three different ways:

- With increasing reaction temperature, the concentrations of CH_4 and light hydrocarbons decrease [23, 25, 28, 31, 36, 43, 46]. This is due to the enhanced steam methane reforming (SMR) reaction [25, 30, 31, 44, 46, 48], the CH_4 decomposition reaction [25] and the thermal cracking reaction [28, 31, 44], all of which consume CH_4 and light hydrocarbons. Raman et al. [21] and Lv et al. [22] concluded that this change as a function of temperature was approximately linear.
- The CH_4 concentration is not significantly influenced by the temperature [19, 41].
- The CH_4 concentration increases slightly with temperature [32, 37, 45], which indicates that the cracking reactions (generation of H_2 and light hydrocarbons) prevail over reforming reactions (generation of H_2 and CO from the reforming of light hydrocarbons) at higher temperatures [32, 37].

The following Figure 2-2 demonstrates the upward and downward trends of CH_4 concentration as a function of the temperature.

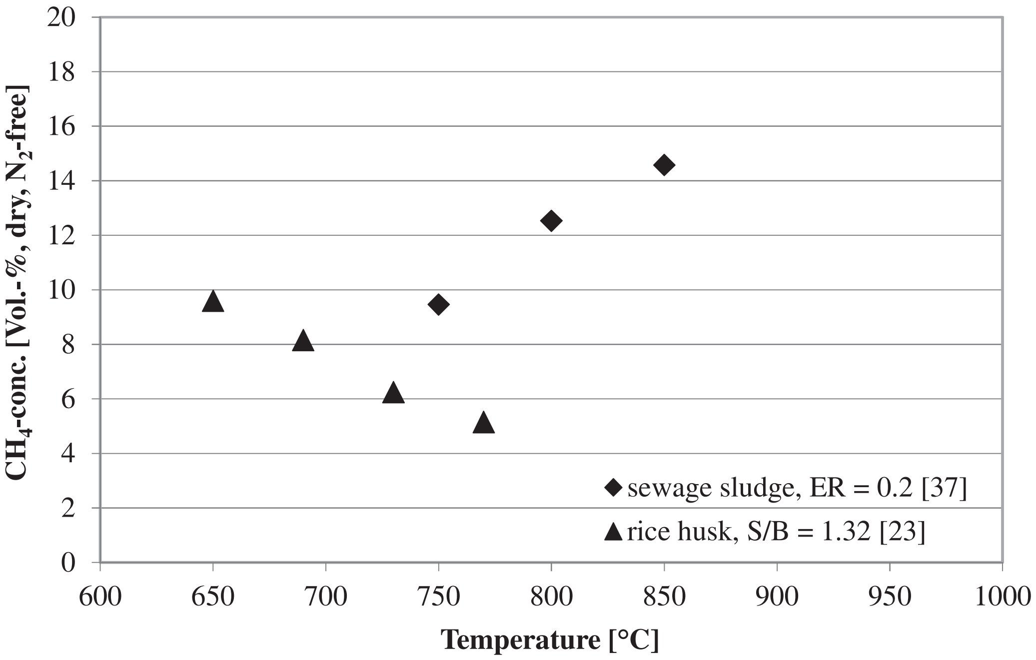


Figure 2-2: CH_4-concentration as a function of temperature.

The change of fuel gas lower heating value (LHV) with temperature depends largely on the concentrations of CO, CH_4 and light hydrocarbons because of their higher calorific values in comparison to H_2. As a result of the aforementioned different trends of CO, CH_4 and light hydrocarbon concentrations in response to temperature, some studies showed that the LHV decreased with increasing gasification temperature [9, 21, 22, 25-27, 31], while others confirmed that the LHV increased with temperature [32, 34, 40, 41, 48, 50].

Cold gas efficiency (CGE), which is also named as energy efficiency, energy recovery ratio or thermal efficiency, increases with temperature [19, 28, 31] and is shown to have an approximately linear relationship to temperature [21, 24, 28, 45, 48]. Similarly, carbon conversion efficiency (CCE) increases with temperature [22, 25, 27, 31, 45] because of the enhanced endothermic char gasification reactions at higher temperatures and therefore higher carbon conversion to combustible gases. However, Lahijani et al. [48] also determined that the increase of temperature beyond 850 °C did not enhance carbon conversion through the Boudouard reaction. At last, steam conversion efficiency (SCE) also increases with the gasifier temperature [22, 24] as a result of the enhanced steam reforming reactions at higher reaction temperatures.

In conclusion, high temperature is favorable to a better fuel conversion in the gasification process, notwithstanding practical problems such as expensive heat supply or process instability because of high potential of bed agglomeration. The concentrations of CO,

CH_4 and light hydrocarbons in the fuel gas are comprehensive functions of all operating parameters as well as reaction networks and, therefore, do not simply follow the increase or decrease of temperature.

2.1.2 Gasification Agent

Most commonly, air is used as gasification agent. However, the large amount of inert nitrogen present in the air dilutes the fuel gas (typically above 50 Vol. %). As a result, the fuel gas has a low content of combustible gases and consequently a low gas lower heating value (LHV). Steam is used to replace air as a gasification agent to improve fuel gas quality, which eliminates the nitrogen dilution effect and enhances the steam reforming reactions as well as the water-gas shift (WGS) reaction. However, the steam gasification process is largely endothermic and requires external heat. Much research work has been focused on using the mixture of steam and oxygen or, more often, the mixture of steam and air or oxygen enriched air as the gasification agent because the heat produced from the combustion can support the steam gasification reactions. Aiming to reduce CO_2 emission from flue gas of coal-fired power plants, the feasibility of adding CO_2 to steam gasification process or using it as the only gasification agent for bio-char gasification is also under investigation.

Air

The fuel mass flow rate, the equivalence ratio (ER) and the stoichiometric air to fuel ratio (SR) determine the amount of air required for gasification. ER is defined as the actual air to fuel ratio divided by SR that is required for complete combustion:

$$ER = \frac{\frac{\text{air}}{fuel}\,[\frac{kg}{kg}]}{SR} \tag{2-1}$$

ER determines the fuel gas composition and its tar content, gas lower heating value (LHV), gas yield as well as reaction temperature. With increasing ER, the concentrations of combustible gases in the fuel gas decrease [41, 44, 51-53] because of the increasing available oxygen for the exothermic combustion reactions with char or combustible gas. As a result, the temperature in the reactor increases [51] and the tar content in the fuel gas as well as the gas LHV decrease [29, 41, 50, 51, 53-55]. Since the reaction temperature largely depends on ER, the influence of ER on the gasifier performance could be regarded as the effect of temperature [30]. Nonetheless, the gas yield increases with ER [29, 41, 50, 51, 56] probably because of the greater gas production rate from the initial fuel devolatilization, the char gasification, the tar cracking and steam reforming, which are more rapid at higher ERs (i.e. at higher temperatures) [51].

The value of ER in the literature ranges from 0.07 [29] to 1 [56], whereas the recommended ER range is between 0.2 and 0.4 [41, 55, 57]. Gasification at lower ER produces a fuel gas with high energy content. However, the fuel gas also contains a large amount of tar and, thus, a substantial effort is required in the gas cleaning steps. Therefore, values for ER lower than 0.18 are considered to be impractical [41]. Gasification at higher values of ER results in a lower amount of tar in the fuel gas but at the cost of lower fuel gas LHV [41, 55]. An optimal value for ER is different for every individual gasifier under different operating conditions. Kaewluan et al. [58] investigated the potential of synthesis gas production from air gasification of rubber wood chip using a pilot-scale bubbling fluidized bed (BFB) gasifier and determined that the highest carbon conversion efficiency (CCE) and cold gas efficiency (CGE) were achieved at ER of 0.38. In another study, Skoulou et al. [49] used a laboratory-scale BFB reactor for air gasification of olive kernels and concluded with an optimum ER of 0.2 at a temperature of 750 °C. They claimed that a further increase of ER deteriorated gas quality and reduced the hydrogen content as well as gas LHV.

Steam

For steam gasification, the parameter named steam to biomass ratio (S/B) is often used and defined as the steam mass flow rate, including the moisture from fuel, divided by the fuel mass flow rate at its dry and ash free (daf) condition:

$$\frac{S}{B} = \frac{steam\,[\frac{kg}{h}]}{biomass\,[\frac{kg}{h},\ daf]} \tag{2-2}$$

The presence of steam in the biomass gasification process favors the hydrogen yield [23, 31, 42, 43, 47, 59] and gas yield [23, 42], which increase with S/B. Simultaneously, the concentrations of CO and CH_4 in the fuel gas decreases with increasing S/B [23, 31, 42, 43], so does the tar content in the fuel gas [25, 42, 43]. This is explained by the enhanced water-gas reaction, steam reforming reactions and water-gas shift (WGS) reaction [43, 59]. However, higher S/B could be also disadvantageous because of the necessary heat of vaporization for steam, which leads to low reactor temperature and deteriorates fuel gas quality. Values for steam to biomass ratio (S/B) in the literature vary between 0.2 [21] and 1.7 [23]. Franco et al. [31] carried out steam gasification of three different woody fuels with a laboratory-scale BFB gasifier, in which S/B was varied from 0.4 to 0.85. The S/B of 0.6 – 0.7 was found to facilitate higher energy and carbon conversion, greater gas yields, and higher H_2 yield. However, no optimum S/B was specified in other studies.

Mixture of steam and oxygen or mixture of steam and air/oxygen enriched air

Gil et al. [28] proposed the parameter named gasification agent ratio (GR) for gasification with the mixture of steam and oxygen:

$$GR = \frac{steam + O_2\ [\frac{kg}{h}]}{biomass\ [\frac{kg}{h},\ daf]} \tag{2-3}$$

This parameter should be provided together with the steam to oxygen ratio H_2O/O_2 (mol/mol). Gil et al. [28] gasified pine chips with the mixture of steam and oxygen using a technical-scale bubbling fluidized bed (BFB) facility and varied the GR between 0.6 and 1.6, the H_2O/O_2 between 2 and 3 and at temperatures between 780 °C and 890 °C. Based on the experimental results, they concluded that the best operating condition was at GR from 0.8 to 1.2, H_2O/O_2 at around 3, and the temperature between 800 °C and 860 °C.

In practice, gasification with steam and oxygen turns to be uneconomical, particularly for small-scale BFB units, because an expensive air-separation unit is needed to produce oxygen for the gasification process. Therefore, much more research work [19, 22, 37, 45, 46, 59-64] has been focused on using the mixture of steam and air or oxygen enriched air as gasification agent. In this case, the ranges of equivalence ratio (ER) and steam to biomass ratio (S/B) found in the literature differ greatly from each other, with ER from 0.07 to 0.8 and S/B from 0.4 to 14.29. Similar to the choice of ER, the optimum combination of ER and S/B depends on the individual gasifier configuration and operating conditions. Lv et al. [46] separated the air and steam input position by adding steam to the position above the biomass feeding location. The highest hydrogen yield was achieved at a temperature of 900 °C, ER of 0.22 and S/B of 2.70. A later study of the same research group demonstrated that, while maintaining the temperature at 800 °C and ER at 0.22, the fuel gas composition experienced little variation when S/B was larger than 2.7 [22]. Campoy et al. [64] used the mixture of steam and oxygen enriched air for the gasification of wood pellets in a pilot-scale BFB gasifier and varied ER from 0.24 to 0.38 as well as S/B from 0 to 0.63. The enriched air has around 40 Vol. % of O_2, which can be produced using commercial membrane-based air separators at comparably low cost. Apart from reducing the nitrogen dilution effect, they aimed to increase gasification efficiency and fuel gas lower heating value (LHV). Tests were conducted under simulated adiabatic and auto-thermal conditions to reproduce the behavior of industrial scale BFB gasifier. The optimal S/B was found to be in the range of 0.25 and 0.35.

2.1.3 Fuel Types and Characteristics

To answer the question of whether a biomass fuel can be used for the BFB gasification process, a few factors, i.e. fuel type, characteristics, pretreatment necessity and gasification performance, should be considered. A large number of biomass fuels (with or without pretreatment) were tested in BFB gasifiers. Most of these fuels were municipal and industrial wastes as well as agricultural and forestry residues. Others were chosen because of their abundance in the local area with large-scale plantation. In this study, they are categorized into seven groups (Table 2-1): waste, residue from food processing industry, woody residue, agricultural residue, energy crop, mixed fuel and others.