R.E.M. (Rekayasa Energi Manufaktur) Jurnal | Vol.7 no.2/2022
ISSN online (2528-3723)
http://doi.org/10.21070/rem.v7i2.1645

Design of a Gasifier with Microwave-Based Technology with Steam and CO2 As Gas Agent to Produce Syngas

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Article history: Received: 26 July 2022 | Revised: 1 November 2022 | Accepted: 10 November 2022

Abstract. *This research is motivated by the increasing gas emissions produced by industrial, automotive, and household activities, which mostly use fossil energy as an energy source. CO2 capture is introduced to the use of gasification technology in an effort to reduce CO2 emissions, which are one of the causes of the greenhouse effect. The role of microwave is also introduced as an effort to increase thermal efficiency and increase production and quality of syngas and its role in reducing tar which is known to be high in biomass gasification. The utilization of water vapor is also clearly disclosed, as its effect on syngas products, especially hydrogen gas. The role of parameters that affect the gasification process is analyzed to see which variant has the best role in improving the quality and quantity of syngas. Research development opportunities are presented by looking at research gaps and prospects.*

Keywords - *CO2 capture, microwave, syngas, gasification*

INTRODUCTION

Greenhouse gases (GHG) mostly come from carbon dioxide, nitrous oxide, and methane, which have a molecular structure that is able to absorb a certain amount of heat, and this capacity regulates the effects of global warming. The percentage of gases that contribute to the greenhouse effect the highest is CO2 (53%), methane (17%), chlorofluorocarbons / CFCs (12%), nitrous oxide (6%), and others (12%)[1]. The net emission of greenhouse gases over the 25-year period (1990-2015) caused by human activities increased by 43%. CO2 emissions accounted for about three-quarters of total emissions, an increase of 51 percent over the period [2], [3]. The use of fossil energy has the potential to increase the concentration of greenhouse gases, especially carbon dioxide (CO2).

The Optimum level for CO2 in the atmosphere is 350 ppm. The safe limit for CO2 levels in the atmosphere is 350 ppm. The concentration of carbon dioxide (CO2) in the atmosphere has increased from about 277 parts per million (ppm) in 1750 at the beginning of the industrial era [4]. This condition continues to increase along with the growing industry in the world. In 220, the concentration of CO2 reached 412.4 + 0.1 ppm, and in 2021, it reached 414.7 ppm. When compared to the pre-industrial era, there has been an increase of 50% due to the release of carbon into the atmosphere [5]. The use of fossil energy is currently still the main energy source, so if this continues, it is estimated that it will continue to increase.

In Indonesia, power and gas plants are the largest contributors to CO2 emissions in Indonesia during the 2015-2019 period. Transportation is the second largest contributor to CO2 emissions, while the Manufacturing Industry is the third largest contributor in Indonesia [6]. According to (Van Heek, 2017) [7], The first cause of GHG emissions is activities related to energy generation at power plants that use fossil fuels such as minerals, coal, natural gas, and oil. Second is traffic and transportation, and third is agriculture, fourth is the manufacturing industry, and fifth is construction activity. For this reason, it is important to take planned steps to reduce CO2 gas emissions. Carbon dioxide mitigation can be done by using more efficient energy, replacing fossil fuels with others with less carbon content, and using renewable energy solutions [8]. CO2 capture technology offers a solution for reducing gases that cause the greenhouse effect [8], [9].

Biofuel is a favorite energy because of its ability to be stored in solid, liquid or gas form. This is a distinct advantage compared to other renewable energies such as energy from wind, water and the sun. The three energies tend to fluctuate and intermittently are influenced by weather and regional conditions. For this reason, biofuel is considered superior because it implies energy stability. The use of biomass as a carbon-neutral alternative energy source has also been extensively studied to reduce widespread CO2 pollution [10]. Biomass conversion through the hydrothermal process has the ability to fluctuate raw materials with high conversion rates and more controlled products [11].

Gasification is a thermochemical conversion process that partially oxidizes carbon materials to produce syngas with the largest gas fractions being N_2, CO, H_2, CO_2 achieved by reacting biomass or coal-based raw materials at high temperatures (range temperature 600 – 900 °C) [12], [13].

The by-products of the gasification process are tar and charcoal/ash with gasifying air agents [14], [15], [16], steam [17], and CO_2 [18]. The resulting syngas can then be used for energy recycling or the manufacture of chemicals, while charcoal/solid ash has the potential to be used as fertilizer [19], [20], [21].

Steam gasification will produce syngas with an increased hydrogen composition through the reaction of carbon gas with steam (C + H2O CO + H2). Another reaction that can occur between syngas and steam is the process of reforming methane with steam (CH4 + H2O CO +3H2) and the displacement reaction of carbon monoxide gas with steam (CO + H2O CO2 + H2). The process is known as the water-gas shift reaction (WGSR). The result of the reaction that occurs between syngas and steam will increase CGE (Cold Gasification Efficiency) [22],[23].

The use of H2O steam is expected to increase the syngas and also increase the hydrogen content in the produced syngas. On study [24], H2O can reduce the particle size of CaO and increase its dispersion on the surface of the charcoal so that the catalytic effect of calcium can be much more effective.

Microwave is a type of non-ionizing electromagnetic radiation that lies between radio and infrared waves, is limited by a frequency between 0.3 and 300 GHz, and has a wavelength of 0.001–1 m GHz. [25], [26], [27].
Many gasification operational parameters have a great influence on the transformation to syngas, such as the type of reactor [28], [29], [30], operating temperature, equivalence ratio (ER) [31], [32], [33], and steam/biomass ratio (S/B) [34], [35], [36]. The gasification operating temperature has a direct effect on the efficiency of the process [37], [38], [39], [40], [41].

METHODS

This study uses the literature review method. Journals related to the topics analyzed. On Google Scholar with the keyword "carbon capture," there are 1,710 articles, and as many as 457 articles in the last 3 years related to articles with that keyword. On gasification technology, we also tried to explore articles related to "Gasification carbon capture" there were 99 articles in the last 3 years. Meanwhile, with the keyword "gasification carbon capture microwave", 27 articles were found. Although it is not a new topic, in the last 3 years, it is a very interesting topic to be developed in future research.

RESULTS AND DISCUSSION

A. Effect of Feedstock type

In most cases, biomass consists of cellulose, hemicellulose, lignin, and other components. We can find a lot of cellulose content in biomass from wood and straw from various types of plants, as shown in table 1. In comparison, high lignin content is found in plant components such as shells and several types of wood. The selection of the right type of biomass greatly affects the production of syngas during gasification, where the ratio of hemicellulose and cellulose to lignin is directly proportional to the content of syngas produced [30].

The following is data on several types of biomass containing cellulose, hemicellulose, and lignin and their ratios.

Table 1. Composition of several types of biomass

Biomass Types	Cellulose (%)	Hemi cellulose (%)	Lignin (%)	Others (%)	Ratio
Rice straw	30	25	12	33	4.58
Wheat straw	40	28	17	15	4
Bagasse	38	39	20	3	3.85
Hardwood	39	35	20	7	3.7
Deciduous plant	42	25	21.5	11.5	3.12
Pinewood	42.1	17.7	25	0	2.39
Softwood	41	24	28	7	2.32
Spruce wood	41.1	20.9	28	0	2.21
Almond shell	25	27	27.2	0	1.91
Oakwood	34.5	18.6	28	0	1.9
Sunflower seed hull	26.7	18.4	27	0	1.67
Coconut shell	24.2	24.7	34.9	0	1.4

Cellulose, hemicellulose and lignin fractions present in the biomass feedstock are degraded in different temperature ranges, respectively 305-375 °C, 225-325 °C, and 250-500 °C during gasification [42].

B. Effect of Steam Ratio on Feedstocks

Water as a carrier gas in the gasification process is very influential on the syngas produced. In gasification, the use of water can be done in situ or as steam that is imported into the gasification reactor.

The in-situ method is mostly used on biomass, considering the high water content of the biomass. In comparison, the type of water that is fed into the gasification reactor is generally divided into ambient water, subcritical water, and supercritical water.

The hydrothermal liquefaction process simultaneously has a purpose, namely as a reactant and also as a catalyst. This is what supports the increase in high efficiency in the pyrolysis or gasification process. Water at conditions close to the critical point, namely at critical pressures and temperatures as in table 2 is able to produce different properties than conditions below the critical point. Under these conditions, water has a low viscosity with high solubility of organic substances. This is what makes subcritical water able to help the reaction occur quickly and as a good medium that is homogeneous and produces high efficiency [43], [44], [45], [46]. This is what makes many studies try to use subcritical water as a medium to increase efficiency through 2 functions, namely as a solvent and reagent medium in the gasification and pyrolysis processes. This applies not only to sub-critical water, but also to supercritical water which tends to have a higher solvent ability. However, the use of supercritical on a lab scale is still not widely done by researchers, this is a more complex design with the right material selection due to high operating conditions at pressure and temperature.

Table 2. Water properties based on the operating conditions [47]

	Temp. T (°C)	Pressure P (Bar)	Density ρ (kg/m3)	Dielectric constant, ε (F/m)	Ionic product, (p kW)	Heat capacity Cp (kJ/kg.K)	Dynamic viscosity, (mPas)	Heat conductivity λ (mW/m.K)
Ambient Water	25	1	997.45	78.5	14.0	4.22	0.89	608
Steam	400	1	3	1		2.1	0.02	55
Subcritical water	250	50	800	27.1	11.2	4.86	0.11	620
	350	250	625.45	14.07	12	10.1	0.064	
Supercritical water	400	250	0.17	5.9	19.4	13	0.03	160
	400	500	577.79	10.5	11.9	6.8	0.07	438

Steam is used as a carrier gas. In this study, steam was used to increase the concentration of hydrogen (H2). Another study states that in the treatment using H2O steam, it is possible for a secondary water gas reaction to occur. This reaction is endothermic with lower enthalpy H (90.2 kJ/mol) than the Boudard reaction (172 kJ/mol) as well as the deformation reaction of methane (242 kJ/mol) [48].

The increase in gasification temperature also supports two endothermic reactions, namely dry reformation and vapor reformation in methane, where a decrease in CH4 concentration occurs with increasing temperature. Research on the effect of the steam/raw material (biomass) ratio is very large, and the optimum range is from 0.5 to 1.2 [42], [49], [50]. So that it can be considered in gasification research variations in the steam/biomass ratio, preferably in this value range.

C. Microwave Effect

The gasification process generally uses conventional heating, namely using, electric heating. Microwave technology is interesting to be developed in the process of hydrogen-rich gas from gasification and co-gasification. One of the interesting things is that not all biomass can be effectively microwaved. Microwave heating is widely used in the gasification process because of its advantages in providing more energy-efficient and instant heating as well as the ease of temperature control [51], [52], [53]. However, not all types of biomass can be effectively used in a microwave, where materials with a value of tan <0.1 have a low ability to use microwaves. The material will only absorb microwaves, but small ones are converted to heat. Material with a value of > 0.5 has a good ability to use microwave tools [54]. So that in selecting the type of biomass, it is necessary to pay attention to the value of tan or the dielectric constant to determine whether the biomass will be effectively used in microwave equipment. Biomass such as coconut activated carbon has a dielectric constant, so its use is expected to be effective in helping the gasification process using a microwave [55], [56].

It is very well used to support the reactions that occur in the reactor with a microwave heating system. Carbon material has a good dielectric constant or has very good receptor properties compared to other biomass materials with a dielectric loss tangent range of about 0.02-2.95. This can be an opportunity for research branches that want to develop microwave technology as a heater in gasification systems [56]. Charge carrier particles that do not have a partner due to phase changes by an electric field cause a pile on the surface and release their energy in the form of heat, known as the Maxwell-Wagner theory or interfacial polarity. Maxwell-Wagner can describe well how the polarization mechanism of dipolar particles that generate heat in water or organic solvents [57], [58]. The idea of using activated carbon from charcoal produced from various biomass can be a good research opportunity in the development of microwave technology. So the researchers predict that the development of activated carbon from biomass in the area as an abundant renewable energy source is a good research opportunity. Research on activated carbon has also been carried out, such as material from coconut shells, palm oil shell waste, rice husks, etc. Microwave technology is expected to overcome the problem of heterogeneity in biomass sources which, although abundant, have heterogeneous and fluctuating properties with high water content. The use of temperature variations at a temperature of 650-900 C can be an alternative in developing microwave technology.

D. Catalyst

Catalysts increase the rate of a reaction in a slightly different way than other methods of increasing the rate of a reaction. The function of the catalyst is to lower the activation energy so that most of the particles have sufficient energy to react.

To understand more about catalysts, table 3 is presented on how the chemical reactions that occur in catalysts for thermochemical processes are presented.

Table 3. Chemical reactions of catalysts in thermochemical processes

Catalytic	**Reaction**		**Reff**
Calcium (Ca)	WGS (Water Gas Shift) reaction $CO(g) + H_2O(g) \rightarrow CO_2(g) + H_2(g)$	[1]	[59]
	CO2 adsorption (carbonation reaction) :		
	$CaO(s) + CO_2(g) \rightarrow CaCO_3(s)$	[2]	
	Pada suhu tinggi (Kalsinasi) :		
	$CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$	[3]	
	SEHP (Sorption-Enhanced Hydrogen Production) :		
	$CO(g) + CaO(s) + H_2O(g) \rightarrow H_2(g) + CaCO_3(s)$	[4]	
	$Ca(OH)_2(s) + CO_2(g) \Leftrightarrow CaCO_3(s) + H_2O(g)$	[5]	
Oxygen Carrier	$2CaO+2Fe+3H_2O = Ca_2Fe_2O_5+3H_2$	[6]	[60]
	$2CaO+2Fe+3CO_2=Ca_2Fe_2O_5+3CO$	[7]	
	$CaO+2Fe+3CO_2=CaFe_2O_4+3CO$	[8]	
	$CaO+2Fe+3H_2O = CaFe_2O_4+3H_2$	[9]	
	$Fe+H_2O = FeO+H_2$	[10]	
	$CaO + CO_2=CaCO_3$	[11]	
Kalium (K) c	$K\text{-}C_{site} + CO_2 \rightarrow K\text{-}C-O + CO$	[12]	[61]
	$K\text{-}C-O \rightarrow K(s) + CO$	[13]	
	$K(s) + C \rightarrow K\text{-}C_{site}$	[14]	
	$K_2\text{-}CO_3 (s, l) + 2C(s) \leftrightarrow 2K(g) + 3CO(g)$	[15]	[62]
	$2K(g) + CO_2(g) \leftrightarrow K_2\text{-}O (s, l) + CO(g)$	[16]	
	$K_2\text{-}O (s, l) + CO_2(g) \leftrightarrow K_2\text{-}CO_3(s, l)$	[17]	
Ni	$NiO + C (char) \rightarrow Ni + CO$	[18]	[63]
	$Ni + CO_2 \rightarrow NiO + CO$		
	$NiO + CH_4 \rightarrow Ni + CO + 2H_2$		
	$NiO + H_2 \rightarrow Ni + H_2O$		

Alkali metal-based catalysts are widely used in gasification processes such as K, Ca, Mg or transition metals such as Ni. This catalyst in its use can be used alone, such as K_2CO_3, $CaCO_3$, CaO, MgO, CeO_2, MnO_2, and Fe_2O_3 but mostly combined with other alkali metals such as CaO/MgO [59], Ni/MgO [64], Ni/CaO (Irfan et al. 2021), Ni/TiO_2 [65] , K_2CO_3/$CaCO_3$[66], K_2CO_3/SiO_2 [67].

E. Effect of Temperature

Cai et al. 2021a [68] studied the co gasification of biomass at operating temperatures down to 800−900 °C. The synergistic effect increased at lower equivalent ratios in the 0.1−0.2 range and at increasing temperatures (800−900 C). The synergistic effect tends to decrease as the equivalent ratio increases, which is in the range of 0.3−0.4. N A Ahmad et al. 2021 [61] stated that optimal conditions were achieved at the vapor/CO_2 ratio taking place at 0.028 C, temperature 850 C. Under these conditions, the conversion of CO_2 and Char was 92% and 85%, respectively.

At high-temperature operating conditions, the aim is to reduce tar production, which can cause contaminants in the syngas. At low operating temperatures of 500-600 ^oC, the potential for tar production will be very high [69]. At low-temperature operating conditions with high tar, the role of a catalyst that is able to accelerate the reaction rate and at the same time can break down tar becomes very important.

At low-temperature operating conditions with high tar, the role of a catalyst that is able to accelerate the reaction rate and at the same time is able to break down tar becomes very important.

Several studies have shown that at higher temperatures, around 850-1000 ^oC the optimum CEG effect is obtained. Research [70] conducted co-gasification of petroleum coke and biomass at a temperature of 900 C - 1100 C. The synergistic effect on the co-gasification reactivity gradually weakened with increasing temperature from 1000 C to 1100 C. This phenomenon is strongly related to the appearance of glass-state potassium-rich liquid biomass ash and the weakest inhibitory effect on the active K transformation during co-gasification at temperatures higher than 1000 ◦C.

Gasification of bagasse in supercritical water with alkaline catalysts (Raney nickel, and activated carbon) for bagasse biomass at a reaction temperature of 400-800 ◦C was carried out by [71]. Increasing the reaction temperature causes a significant increase in hydrogen yield. The highest amount of hydrogen (75.6 mol kg-1) was reached at 800 ◦C. The study carried out a co-gasification test on biomass from cotton stalks combined with ash with temperatures varying from 750 C to 1050 C with intervals of 100 C. Results The results showed an increase in gas increase in co-pyrolysis/gasification due to re-contact between volatiles and half-char, both of which reached a maximum level at 80% gas production mixing ratio at 950 C. In the test of oil palm shell gasification (OPS) by [61], a temperature of 700-850 C using steam/CO_2. The results showed that optimal operation was achieved at a steam/CO_2 ratio of 0.028 and at the highest temperature by conversion of char and CO_2. Increasing the steam flow at maximum temperature increases the H_2/CO Ratio by 22%. A mixture of CaO/MgO sorbents was used for the sugarcane leaf gasification catalyst, which was tested at different devolatilization temperatures (400-800 ◦C) and gasification temperatures (600-800 ◦C). Increasing the gasification temperature above 600 ◦C gives higher H_2 yields but leads to lower H_2 concentrations. So it is clear from several studies that at high temperatures around 850-1000 ◦C good gasification performance is obtained.

The increase in temperature also affects the gas yield and carbon conversion efficiency at a high equivalent ratio value of more than 0.3. Another positive thing is that it can inhibit the agglomeration process at an increasing ratio of biomass such as straw This is interesting because the agglomeration holding temperature can reach 900 C. M. Gao, Z, 2016 [24] Testing the co-gasification of waste biomass from waste fuel RDF and coal at 800−900 C using calcium (Ca) and a mixture of carrier gas H_2O/CO_2. The occurrence of agglomeration was found to weaken with increasing temperature and at a temperature of 900 C this effect was no longer found.

F. Effect of CO2

Carbon Capture (CC) is currently an interesting research topic and is considered an excellent method of reducing CO_2 emissions. The carbo capture system draws attention from academics, researchers, policy makers (government) in overcoming the problem of CO_2 emissions which are currently increasing due to the use of fossil fuels in industry, transportation or households. This technology is considered appropriate and is one of the solutions besides the use of new renewable energy in the world [73]. According to the International Energy Agency (IEA), the volume of CO_2 emissions due to burning fossil fuels accounts for 56% of all global emissions. Carbon Capture and Storage (CCS) is a global warming mitigation method by reducing CO_2 emissions into the atmosphere. This technology has the stages of the process of separating and capturing CO_2 from the source of flue gas emissions from the combustion reaction. Furthermore, the captured CO_2 transports to a storage area (transportation), and storage to a safe place (storage). Absorption technology is a CO_2 separation and capture method that is well known by the power generation, petrochemical or transportation industries. CO_2 capture is commonly used to convert gaseous emissions into gaseous energy products such as hydrogen which is carried out on a laboratory or commercial scale. In fact, gas storage with a large volume of CCS is considered less effective. Thus, the mitigation pattern in the energy sector has begun to shift to CO_2 valorization technology. This technology has become a value-added product in product improvement, but several obstacles are still being faced and become an interesting research topic for carbon capture technology [74]. There are three Carbon Capture systems used in combustion technology to release CO_2 gas emissions. The first is 1) Post-Combustion Capture (PCC). PCC is considered an ideal method for thermal power generation systems that use fossil fuels (gas, solid, liquid), biomass, municipal solid waste or other energy sources. In this PCC technology, exhaust gas or steam from complete combustion is produced by gas consisting of CO2, N2, H2O and their combination. In incomplete combustion of gas and lack of space, it can produce other gas emissions such as CO, CxHy, Nox, dioxin gas. The steam used as turbine propulsion energy is in the form of enthalpy, then the exhaust gas enters the PCC process. At this stage, the flue gas is separated and isolated CO2 from nitrogen gas and water. At this stage it is considered to have its own problems because of the complexity of separating CO2 from other gaseous elements. This makes research on PCC technology currently quite in demand. One of the challenges faced is the level of CO2 in the combustion exhaust gases is relatively small. This is economically unprofitable because the energy and costs used are relatively high [75], [76].

The second carbon capture technology is pre-combustion capture (PrCC). This technology uses an oxygen or air control system at high temperatures. Gasification using low level oxygen reforms the flue gas by the gasification process. This technology is usually carried out in integrated gasification combined cycle power plants (IGCC). This process produces syngas or biosyngas in biomass-based fuels. The product gas resulting from the gasification process consists mainly of containing mainly CO, CO2 and a small amount of CxHy. Syngas can undergo a water gas shift reaction process, the steam then converts the syngas into H2 and CO2. Concentration of CO_2 in the range of 15-50% [76].

The third technology is oxyfuel combustion capture (OCC). In this technology there is a combustion process using pure oxygen for the oxidation process which comes from air with an oxygen content of about 98%. The flue gas produced from this process contains a higher concentration of CO2 and a relatively small nitrogen gas pollutant content. This process is better than using air for combustion with a N2 content of 79.9%. The use of pure oxygen causes high operating costs. This is due to the process of purifying oxygen from the air using a cryogenic system that uses relatively high energy for the process of separating oxygen from the air at very low temperatures. The technology of oxygen separation by oxidation of metal compounds is currently attractive and promising and interesting to research because of the use of less energy and low operating costs.[77], [77].

PrCC type carbon capture technology is currently widely applied to gasification systems. This is a very promising thing considering the gasification technology which uses a lot of energy waste from biomass or municipal solid waste (MSW). However, the problem at this time is the formation of high CO2 and Tar and fluctuations in the nature of the biomass in the gasification process which makes the operation and maintenance of the equipment complicated [78]. Another interesting thing about the gasification system using steam is that it is in situ. The high water content of biomass and MSW is also a problem. However, an in situ system on a gasification system that uses steam can make a solution to produce hydrogen-rich syngas [79].

CONCLUSIONS

In syngas production, the roles of research variants are very diverse. In general, the temperature variance affects the reduction of tar at increasing temperatures. However, materials such as catalysts are very easy to agglomerate at temperatures that are too high. In the use of steam, the greater the percentage of steam to biomass, the greater the production of hydrogen gas, but on the other hand, the temperature also decreases because of the energy absorbed by the steam. CO2 has been proven to be used to convert certain gases that have low heating values and can be decomposed into gases with high heating values, namely CO and H2. In this case, the role of the catalyst is to decompose tar or other complex gases into gases with high heating values.

ACKNOWLEDGMENTS

We would like to thank Sultan Ageng Tirtayasa University for supporting this research through the Beginner Lecturer Research grant. Also, colleagues who have played an active role in carrying out this research so that it can run as planned.

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