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Simulation Study for Syn-Gas Productivity of Open Top Downdraft Gasifier Using Wood Sawdust Feedstock by ASPEN Plus

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ABSTRACT

Wood sawdust feedstock is one of commodity of furniture industrial waste in Indonesia. It could be used for biomass feedstock for syn-gas producing with gasification process. Wood sawdust could be alternative ways for replacing other biomass feedstock that hard to find for biomass gasification processing, it has good high heating value (HHV) of abouts 18.75 MJ/kg. Besides that open top downdraft gasifier is one of a kind biomass gasifier/reactor for syn-gas producing. It had better with the other gasifier for syn-gas producing; such as cross draft gasifier and updraft gasifier because for micro-grid electricity it has lower cost for designing and maintaining. Syn-gas is a synthetic gas that contains several elements of hydrocarbons, such as CO (carbon monoxide), CH_4 (methane) and H_2 (hydrogen). It could be useful for combining with internal combustion engine for producing micro-grid electricity. Syn-gas could be alternative fuel to replace gasolines or diesels fuel for internal combustion engine that converted to electrical generator as prime mover power. At this simulation study we get the result of mole fractions for syn-gas productivity from wood sawdust feedstock by using ASPEN Plus software is CO (1.622%), CH_4 (6.722%), H_2 (12.448%). At the end of the calculations we get HHV of syn-gas is 4.47 MJ/Nm^3, gasification efficiency (X_{cge}) is 20% and amount of carbon in wood sawdust that convert to gaseous (X_c) is 0.43%. Simulation study by using ASPEN Plus software could be more useful for resulting syn-gas productivity without any problems. For academic communities, simulation study by using software could be solutions when we have no more cost for practicing in the workshop.

INTRODUCTION

Downdraft gasifiers in design are mostly made with open core or open top types. Therefore, a downdraft gasifier is often referred to as an open top downdraft gasifier. This situation lasts for a permanent gasification cycle. Open top downdraft gasifier or downdraft gasifier is a classification of fixed-bed gasifier which is a type of fluidized gasification mode. In general, there are three types of fixed-bed gasifiers, namely updraft gasifier (counter-current system) with the working principle of flowing gasified gas upward, downdraft gasifier (co-current system) with the working principle of flowing gasified gas downward, and cross draft gasifier with the working principle of flowing gas from gasification perpendicular to the direction of motion of the combustion phase space (oxidation phase) [11].

An open top downdraft gasifier can reduce the tar problem in syn-gas where the gasified primary air is introduced above the oxidation phase during the gasification cycle. Syn-gas flows from the

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bottom of the gasifier, so the fuel and gas move in the same direction. The products released during the pyrolysis phase are converted into gases such as hydrogen (H_2), carbon dioxide (CO_2), carbon monoxide (CO) and methane (CH_4). The main advantage of the downdraft gasifier is that it can produce gas that has a low tar content which is suitable for engine applications [10].

The working principle of the downdraft gasifier is that initially the feedstock (raw material) of biomass is put into the gasifier through the hopper (core), until it fills the entire reactor space. Then the ignition is done, through the air hole in the middle of the surface of the outer wall of the reactor. When the fire has started to burn the biomass feedstock, make sure that all pipe connections, the outer walls of the reactor, cyclone, scrubber and also the blower do not have any leaks. If a leak occurs, this can hinder the gasification cycle, due to a decrease in temperature, making it difficult to obtain syn-gas gasification. Decreasing the temperature could inhibit the thermochemical reactions in each phase of the gasification cycle.

In addition, compared to other biomass gasification systems, the open top downdraft gasifier has advantages that make it easier to apply, including :[12]

1) More than 99.9% of the tar formed from the process of the biomass gasification system does not require tar cleaning.
2) The remaining minerals are mixed with charcoal and ash, so we do not need a cyclone separator.
3) Proven, simple and relatively inexpensive production costs.

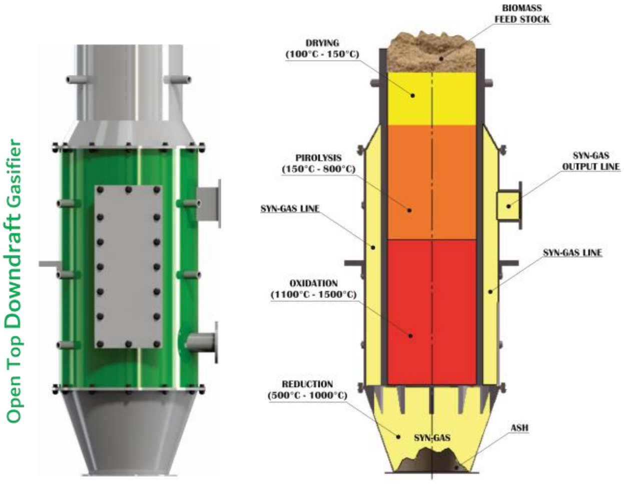


Fig. 1. Scheme of Open Top Downdraft Gasifier in UNSADA Workshop

EXPERIMENTAL METHOD

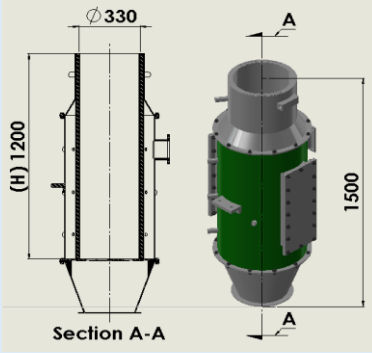
The research material for the process of the biomass gasification system is an open top downdraft gasifier with the use of coarse wood sawdust as a feedstock according to the pre-design test for author's thesis at the Darma Persada University (UNSADA) workshop in Jakarta, 2019. To carry out a simulation using ASPEN Plus, it is necessary to solve the chemical equilibrium in detail. Each phase of biomass gasification must be broken down separately, starting from the drying phase which is input using the RStoic Reactor, then the pyrolysis phase is input using the RYield Reactor, and then the oxidation phase and the reduction phase are input using the RGibbs Reactor [3, 6, 9].

RESULTS AND DISCUSSION

The open top downdraft gasifier specifications are described in the figure 2, Including:

Specification

Open Top Downdraft Gasifier



$H_{reactor}$: 1200 mm = 1.2 m
$\varnothing_{reactor}$: 330 mm = 0.33 m
$V_{reactor}$: A x H
A : $\left(\frac{\pi}{4}\right) x\ D^2$
: $\left(\frac{3.14}{4}\right) x\ 0.332$
A : 0.085 m^2
$V_{reactor}$: 0.085 x 1.2
: 0.102 m^3
Q_n : 1 kWh = 3.6 MJ
η_{gb} : 17 %
ε : 0.3 - 0.4

Biomasss Feedstock

$\rho_{wood\ Sawdust}$: 0.02 g/cm^3 = 20 kg/m^3
$m_{wood\ sawdust}$: 13.1 kg
$HHV_{wood\ sawdust}$: 18.75 MJ/kg
$T_{gasification}$: 6480 s = 108 min = 1.8 hr
$T_{pyrolisys}$: 700 ^oC

Air Density

ρ_{air} : 1.25 kg/m^3

Biomass Stoichiometric Air for Wood Gasification

x = 1.43 $CH_xO_y + zO_2 \Leftrightarrow CO_2 + \frac{X}{2} H_2O$
y = 0.66 with $z = 1 + \frac{x}{4} - \frac{y}{2}$; $z = 1 + \frac{1.43}{4} - \frac{0.66}{2}$
z = (1 + 0.3575) - 0.33 = 1.02
Oxygen Factor = 25 % From Stoichiometric Air
Biomass Stoichiometric Air (SA) ; SA = F x Z
SA = 0.25 x 1.02 = 0.255 $\frac{kg\ O_2}{kg\ Biomass}$

Fig. 2. Specifications of Open Top Downdraft Gasifier

Prior to the main simulation, it is required to fill in the chemical formula properties tab data in the biomass gasification stream cycle are described in the figure 4.

Next, we go to the simulation tab to create a model palette for the biomass gasification stream. Hierarchically, the steps include :[3, 6, 9]

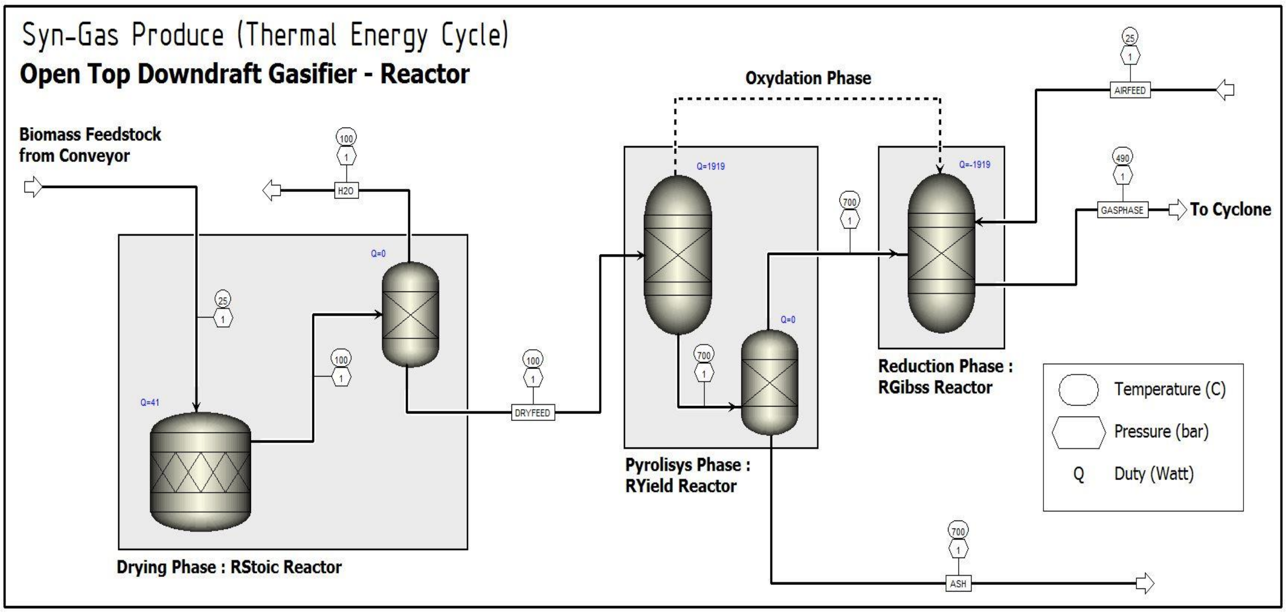


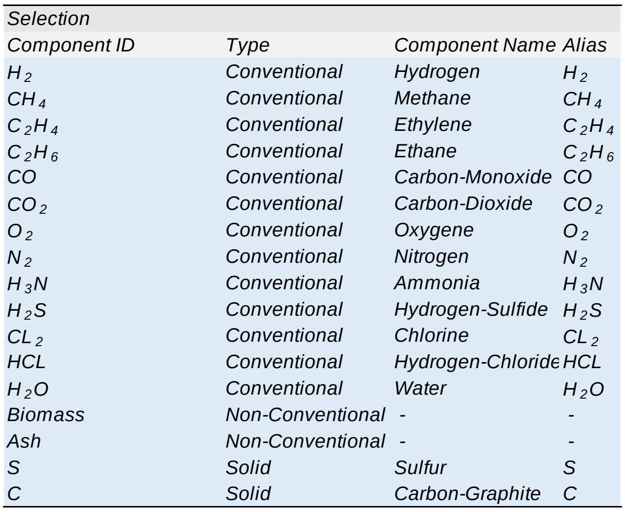
Fig. 3. Simulation Scheme for Syn-gas Productivity of Open Top Downdraft Gasifier Using Wood Sawdust Feedstock by ASPEN Plus

a. Drying Phase

In this step, input data is needed to calculate the fuel consumption rate (FCR) or mass fuel rate from the actual test of the open top downdraft gasifier. FCR could be calculated by the equation :[1]

$$\mathrm{FCR} = \frac{Q_n}{\mathrm{HHV}_{\text{wood sawdust}} \times \eta_{gb}} \qquad (1)$$

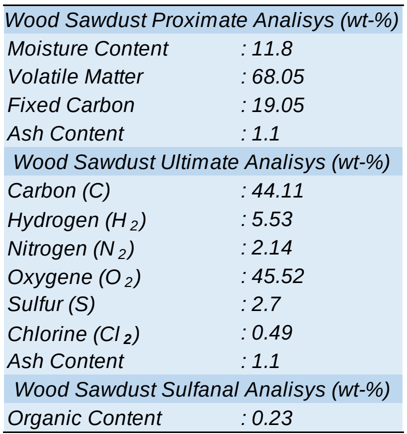
$$\mathrm{FCR} = \frac{3{,}6}{18{,}75 \times 0{,}17} = \frac{3{,}6}{3{,}1875} = 1{,}13 \text{ kg/hr}$$



Selection			
Component ID	Type	Component Name	Alias
H_2	Conventional	Hydrogen	H_2
CH_4	Conventional	Methane	CH_4
C_2H_4	Conventional	Ethylene	C_2H_4
C_2H_6	Conventional	Ethane	C_2H_6
CO	Conventional	Carbon-Monoxide	CO
CO_2	Conventional	Carbon-Dioxide	CO_2
O_2	Conventional	Oxygene	O_2
N_2	Conventional	Nitrogen	N_2
H_3N	Conventional	Ammonia	H_3N
H_2S	Conventional	Hydrogen-Sulfide	H_2S
CL_2	Conventional	Chlorine	CL_2
HCL	Conventional	Hydrogen-Chloride	HCL
H_2O	Conventional	Water	H_2O
Biomass	Non-Conventional	-	-
Ash	Non-Conventional	-	-
S	Solid	Sulfur	S
C	Solid	Carbon-Graphite	C

Fig. 4. Formula Properties of Biomass Gasification Stream Cycle

Furthermore, the proximate and ultimate analysis the input data is needed from the biomass feedstock, namely wood sawdust. Including in figure 5 :[7, 8]



Wood Sawdust Proximate Analisys (wt-%)	
Moisture Content	: 11.8
Volatile Matter	: 68.05
Fixed Carbon	: 19.05
Ash Content	: 1.1
Wood Sawdust Ultimate Analisys (wt-%)	
Carbon (C)	: 44.11
Hydrogen (H_2)	: 5.53
Nitrogen (N_2)	: 2.14
Oxygene (O_2)	: 45.52
Sulfur (S)	: 2.7
Chlorine (Cl_2)	: 0.49
Ash Content	: 1.1
Wood Sawdust Sulfanal Analisys (wt-%)	
Organic Content	: 0.23

Fig. 5. Formula Properties of Ultimate and Proxymate Analysis of Wood Sawdust

To complete the mass balance data in the ultimate analysis, for biomass gasification, 0.49 wt-% Cl (chlorine) was added and 1.1 wt-% Ash as well. Then also added sulfanal analysis for organic content of 0.23 wt-%.

Next, enter the input data on the RStoic Reactor. The input data is described in figure 6, Including :

RStoic Reactor	
Specification	
$T_{\text{drying phase}}$	: $100^{o}C$
$P_{\text{drying phase}}$	: 1 bar
Stoichiometric Reaction	
Biomass content	: Coefficient → -1 = (Q_{out})
Molar Mass $_{\text{biomass}}$	: 1 kg/kmol
Molar Mass H_2O	: 18.01528 kg/kmol
H_2O *content*	: $\frac{\text{molar mass of biomass}}{\text{molar mass of H}_2\text{O}}$ kg/kmol $\frac{1}{18.01528}$ = 0.055508435 kg/kmol
H_2O *in Biomass* (H_2O *Mass-Flow Rate*)	: $\frac{[(\text{moisture content in proximate analisys})\ \text{x}\ (\text{FCR})]}{\text{T}_{\text{drying phase}}}$ kg/hr $\frac{11.8 \text{ x } 1.13}{100}$ = 0.13334 kg/h
Fractional Conversion of Biomass Feedstock	: $\frac{\text{H}_2\text{O mass}-\text{flow rate}}{\text{FCR}}$ $\frac{0.13334}{1.13}$ = 0.118

Fig. 6. The Input Data of RStoic Reactor

b. Pyrolysis – Oxidation – Reduction Phase

In this step, the input data for calculating the air fuel rate (AFR) or air feed is required, namely the amount of air input needed for the actual biomass gasification process from the open top downdraft gasifier. AFR could be calculated by the equation :[1]

$$\text{AFR}_{\text{min}} = \frac{\varepsilon_{\text{min}} \text{ x FCR x SA}}{\rho_{\text{air}}} \qquad (2)$$

$$\text{AFR}_{\text{min}} = \frac{0{,}3 \text{ x } 1{,}13 \text{ x } 0{,}255}{1{,}25}$$

$$\text{AFR}_{\text{min}} = \frac{0{,}086445}{1{,}25} = 0{,}07\text{m}^3/\text{hr}$$

$$\text{AFR}_{\text{min}} = 0{,}07\frac{\text{m}^3}{\text{hr}} = \frac{0{,}07 \text{ x } 1000}{\text{hr}} = 70\ \ell/\text{hr}$$

$$\text{AFR}_{\text{max}} = \frac{\varepsilon_{\text{max}} \text{ x FCR x SA}}{\rho_{\text{air}}} \qquad (3)$$

$$\text{AFR}_{\text{max}} = \frac{0{,}4 \text{ x } 1{,}13 \text{ x } 0{,}255}{1{,}25}$$

$$\text{AFR}_{\text{max}} = \frac{0{,}11526}{1{,}25} = 0{,}09\ \text{m}^3/\text{hr}$$

$$\text{AFR}_{\text{max}} = 0{,}09\frac{\text{m}^3}{\text{hr}} = \frac{0{,}09 \text{ x } 1000}{\text{hr}} = 90\ \ell/\text{hr}$$

Next enter the input data on RYield Reactor and RGibss Reactor. The input data is described in figure 6 and figure 7, including:

RYield Reactor		
Specification		
$T_{\text{pyrolisys phase}}$	: $700^{o}C$	
$P_{\text{pyrolisys phase}}$	: 1 bar	
Yield Composition		
Mass Fraction	: $\frac{\text{Wood Sawdust Ultimate Analisys (wt}-\%)}{\text{T}_{\text{drying phase}}}$	
Carbon (C)	: 44.11/100	= 0.4411
Hydrogen (H_2)	: 5.53/100	= 0.053
Nitrogen (N_2)	: 2.14/100	= 0.0214
Oxygene (O_2)	: 45.52/100	= 0.4552
Sulfur (S)	: 2.7/100	= 0.027
Chlorine (Cl_2)	: 0.49/100	= 0.0049
Ash Content	: 1.1/100	= 0.011

Fig. 7. The Input Data of RYield Reactor

RGibbs Reactor	
Specification	
$P_{\text{operating condition}}$	: 1 bar
Air Feed	
$T_{\text{air feed}}$	: $25^{o}C$
$P_{\text{air feed}}$	: 1 bar
Total Flow Basis	: $AFR_{minimum}$ = 70 L/hr $AFR_{maximum}$ = 90 L/hr
Mole-Fraction	: O_2 = 0.21 N_2 = 0.79

Fig. 8. The Input Data of RGibbs Reactor

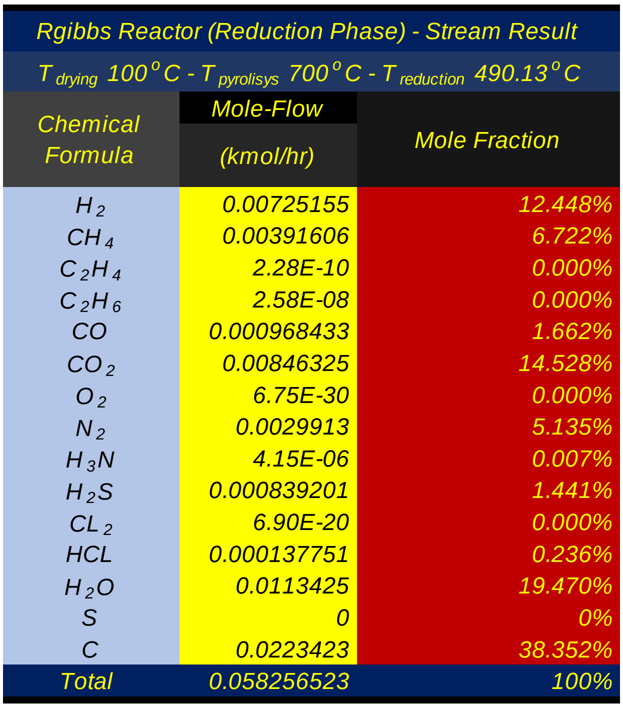
Next, determine the model analysis tool, namely using sensitivity analysis to create a biomass gasification simulation based on AFR_{min} and AFR_{max}. The input data is described in figure 8, including :[5]

Model Analisys Tool (Sensitivity Analisys)	
Manipulated Variable	
Type	: Stream-Var
Stream	: Air Feed
Sub-Stream	: MIXED
Variable	: STDVOL-FLOW
Units	: L/hr
Specify Limits	
Lower	: $AFR_{minimum}$ = 70 L/hr
Upper	: $AFR_{maximum}$ = 90 L/hr
Increment	: 0.75

Fig. 9. The Input Data of RGibbs Reactor

CONCLUSION

The results of the reactor testing simulation from an open top downdraft gasifier are described in several figures, including :

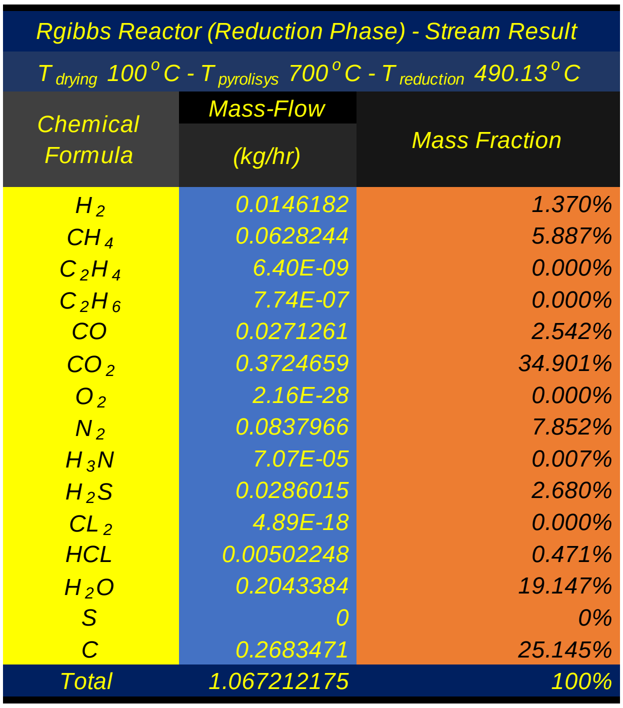


Rgibbs Reactor (Reduction Phase) - Stream Result

T_{drying} 100^{o}C - $T_{pyrolisys}$ 700^{o}C - $T_{reduction}$ 490.13^{o}C

Chemical Formula	Mole-Flow (kmol/hr)	Mole Fraction
H_2	0.00725155	12.448%
CH_4	0.00391606	6.722%
C_2H_4	2.28E-10	0.000%
C_2H_6	2.58E-08	0.000%
CO	0.000968433	1.662%
CO_2	0.00846325	14.528%
O_2	6.75E-30	0.000%
N_2	0.0029913	5.135%
H_3N	4.15E-06	0.007%
H_2S	0.000839201	1.441%
CL_2	6.90E-20	0.000%
HCL	0.000137751	0.236%
H_2O	0.0113425	19.470%
S	0	0%
C	0.0223423	38.352%
Total	0.058256523	100%

Fig. 10. Gas Phase of Biomass Gasification Stream Result (Mole Fractions)



Rgibbs Reactor (Reduction Phase) - Stream Result

T_{drying} 100^{o}C - $T_{pyrolisys}$ 700^{o}C - $T_{reduction}$ 490.13^{o}C

Chemical Formula	Mass-Flow (kg/hr)	Mass Fraction
H_2	0.0146182	1.370%
CH_4	0.0628244	5.887%
C_2H_4	6.40E-09	0.000%
C_2H_6	7.74E-07	0.000%
CO	0.0271261	2.542%
CO_2	0.3724659	34.901%
O_2	2.16E-28	0.000%
N_2	0.0837966	7.852%
H_3N	7.07E-05	0.007%
H_2S	0.0286015	2.680%
CL_2	4.89E-18	0.000%
HCL	0.00502248	0.471%
H_2O	0.2043384	19.147%
S	0	0%
C	0.2683471	25.145%
Total	1.067212175	100%

Fig. 12. Gas Phase of Biomass Gasification Stream Result (Mass Fractions)

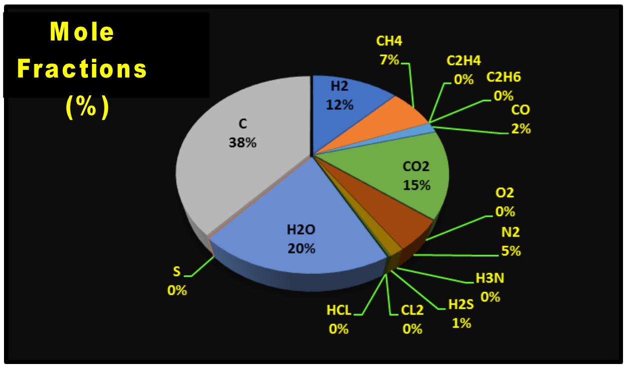


Fig. 11. Chart of Mole Fractions Result

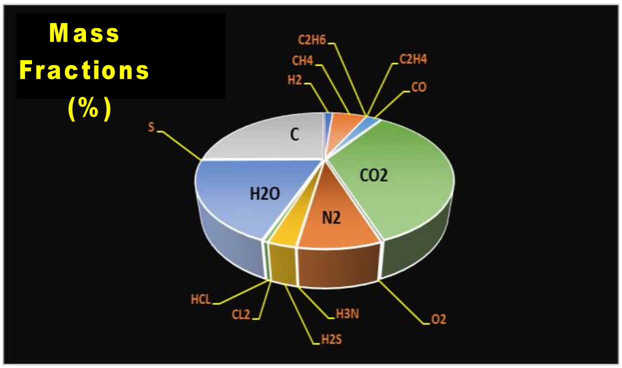


Fig. 11. Chart of Mass Fractions Result

- **mole fractions (%),** T_{drying} 100°C; $T_{pyrolisys}$ 700°C;
  CO : Fig. 10, **CH_4**; Fig. 10, **H_2**; Fig. 10
- **$HHV_{wood\ sawdust}$** : Fig. 2
- **Q_n** : Fig. 2
- **12** : constant [8]
- **A_{mole}** : total mole fractions of carbon → **$CO + CO_2 + CH_4$** ; Fig. 10
- **$m_{wood\ sawdust}$** : Fig. 2; for **$V_{reactor}$** : Fig. 2; → in once time of gasification burner
- **x_c** : mass fractions of carbon (C) on ultimate analisys data ; Fig. 5

$HHV_{syn\text{-}gas}$: high heating value of syn-gas

X_{cge} : gasification efficiency (%)

X_c : amount of carbon in wood sawdust that convert to gaseous

SUMMARY

As the final result, the authors describe the calculation of $HHV_{syn\text{-}gas}$, gasification efficiency (X_{cge}), and carbon conversion efficiency (X_c). This is intended as a comparison of data from actual test results and theoretical testing (ASPEN Plus simulation). Description of the calculation, including :[2, 4, 8]

$HHV_{syn\text{-}gas}$; Based on US National Renewable Energy Laboratory (NREL) as standard value in Normal Cubic Meter (MJ/Nm^3).

$$HHV_{syn\text{-}gas} = (T_{drying}\ 100°C, T_{pyrolysis}\ 700°C)$$

$$= (\text{mol \% CO x } 12{,}63) + (\text{mol \% } CH_4 \text{ x } 39{,}82) + (\text{mol \% } H_2 \text{ x } 12{,}74) \qquad (4)$$

$$= (0{,}01662 \text{ x } 12{,}63) + (0{,}06722 \text{ x } 39{,}82) + (0{,}12448 \text{ x } 12{,}74)$$

$$HHV_{syn\text{-}gas} = (0{,}2099106) + (2{,}6767004) + (1{,}5858752) = 4{,}47 \text{ MJ/Nm}^3$$

$$X_{cge} = (T_{drying}\ 100°C, T_{pyrolysis}\ 700°C)$$

$$X_{cge} = \frac{HHV_{syn-gas}}{HHV_{wood\ sawdust} + Q_n} \text{ x } 100 \qquad (5)$$

$$X_{cge} = (\frac{4{,}47}{18{,}75 + 3{,}6}) \text{ x } 100 = 0{,}2 \text{ x } 100 = 20\%$$

$$X_c = (T_{drying}\ 100°C, T_{pyrolysis}\ 700°C)$$

$$X_{cge} = (\frac{12 \text{ x } A_{mole}}{m_{wood\ sawdust \text{ x } (x_C)}}) \text{ x } 100 \qquad (6)$$

$$X_{cge} = (\frac{12 \text{ x } 0{,}20832}{13{,}1 \text{ x } 44{,}11}) \text{ x } 100 = 0{,}0043 \text{ x } 100 = 0{,}43\%$$

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