Design Calculation Of A100 Kwe Refuse Derived Fuel Gasifier

Suhartono, Nurhadi, Yusuf Suryo Utomo, Imam Djunaedi, Arifin Santosa, Yudi Hidayat

Abstract: A downdraft open top gasifier for refuse-derived fuel (RDF)-pellets was designed as a potential substitution fuel in a modified diesel engine. The gasifier reactor design consideration is intended to produce electricity of 100 kWe. The primary purpose of this paper is to address the gasifier dimensions based on parameters of a diesel engine specification data and an experimental, as well as the simulation results. A small stratified open top gasifier was used to evaluate the performance of RDF-pellets as gasifier feedstocks. The characteristics and gasification performance of RDF-pellets using this small stratified are included. A process model of RDF-pellets gasification was also developed to predict a syngas's qualified to be combusted on the diesel-engine. Based on the points of view of this study revealed that the gasifier diameter and height of downdraft open top gasifier were found in the range of 0.7-1.4 meter and 1.8-3.5 meter, respectively. The thermal power of 225.20 kW in the syngas was obtained from RDF-pellet feed rate of 113.30 kg/hr. to meet 100 kWe of electricity production.The design of the gasifier reactor with this dimension is expected to be feasible to be coupled with a 100 kWe diesel engine for electricity production that is applied in the local municipal waste management.

Index Terms: downdraft, efficiency, gasifier dimension, municipal solid waste, open top gasifier, refused-derive fuel, syngas

1 INTRODUCTION

Refused Derived Fuel (RDF)-pellets is processing products of Municipal Solid Waste (MSW) through shredding and sorting the removable noncombustible material such as metal, glass and other inorganic materials using a series of mechanical processes [1], [2]. This RDF-pellets can be utilized as an alternative fuel and provide economic and environmental benefits. The energy content in the RDF-pellets is converted into a gas phase fuel through the gasification process. The gas-phase product from the gasification process is mainly consists of combustible gases of carbon monoxide (CO), hydrogen (H_2) and methane (CH_4), other gases in the form of carbon dioxide (CO_2), water vapor (H_2O), nitrogen (N_2), some hydrocarbons of carbon particles, tar and ash in lowest quantity. The gas is called as syngas after through ash and tar removal-treatment [3]. The composition and heating value of syngas depends upon the RDF-pellets as feedstocks and processing techniques. The heating value (HV) of the gas varies as low-HV (4–6 MJ/Nm^3), medium-HV (12–18 MJ/Nm^3) and high-HV (40 MJ/Nm^3) propotional to the composition of the gas and oxidizer used [3], [4]. The existing RDF-pellets produced by the Local municipal waste management system in Denpasar, Bali. The RDF-pellets were utilized as a source of electrical energy which is one PT Indonesia Power's new business potentials that related to Waste to Energy (WtE). The current condition of WtE methods is to utilize RDF-pellets as the feedstock of a small downdraft gasifier which produces syngas to be used as fuel on the lower capacity diesel engine. The downdraft fixed bed gasifier coupled to a diesel engine to generate electricity of about 40 kWe. This system could be attractive in the local municipal waste management area (using the site waste).

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The small downdraft gasifier type was seemed to be suitable for gasifier-engine system fueled with RDF-pellets due to produce lower tar gas contents, but lower RDF-pellets consumption. In order to make this installation commercially viable, a process is needed to be scaled-up to 100 kWe. The scale up of the installation be able to decrease equipment investment, so that it will be more efficient and effective in operational and economic aspects. The assignment was initiated to develop a gasifier system to use MSW generated in Bali Province of Indonesia.This work deals with the determination of the gasifier scale-up dimension to reach in a commercial installation yield. It was started with characterized and gasified RDF-pellets as feedstock by using a small-scale stratified gasifier. The prediction of the ideal operational condition in achieving maximum efficiency was simulated using ChemCad software. Regarding the reactor design, the air gasification in the downdraft open top gasifier was an option chosen. Minimal tar cleanup and cyclone separator, proven, simple and low-cost processes are as an advantageous consideration. The open-top gasifier dimension was designed for a 100-kWe diesel engine specification based on experimental and simulation results.

2 MATERIAL AND METHODS

2.1 RDF-Pellets from MSW

RDF-pellets is a solid fuel made of the treatment of MSW to increase the heating value and to create an easily burnt fuel in a gasifier [1], [5]. The RDF-pellet produced from MSW collected at the local districts of Pesanggaran, Bali-Indonesia. The composition of MSW is plastics, rubber waste, paper, and other organic and inorganic material. To produce RDF-pellets, MSW should first be pre-treatment and sorted to remove all non-combustible materials then pressed mechanically into cylindrical particles with an average length and diameter of 2 cm and 1 cm, respectively. The RDF-pellets were sorted and classified into categories including category A (100 % organic), category B (95% organic and 5% plastic) and category C (without sorting). The proximate, ultimate analysis and other physical properties were performed to find out the characterization of RDF-pellets according to ASTM standards. The RDF-pellets characterization comprised the determination of (1) elemental analysis of carbon, nitrogen, and hydrogen, (2) moisture content, volatile matter content, ash content, heating value (HV) and (3) compact particle density, bulk density, macroporosity and ignition time.

2.2 Simulation of RDF-Pellets Conversion Process
The performance of the RDF-pellet gasifier was accomplished by a non-stoichiometric equilibrium model on free energy minimization [6]. The reaction equilibrium calculation was conducted by minimizing Gibb's free energy. The breaking down of RDF-pellets into its constituent elements according to ultimate analysis was the first step of this work in accordance with (1).

$$\mathrm{RDF_{pellets}} \rightarrow \mathrm{aH + bC + cO + dN + eS + ash} \quad (1)$$

The components of the gasification product would consist of H_2, CO, CO_2, CH_4, H_2O, ash, H_2S, and NH_3. An objective function (F_{obj}) was created as the next step as written in the below equations.

$$F_{obj}: \Delta G_{min} = \sum_{j=1}^{s} G_j^0 n_j + \sum_{j=s+1}^{r} \sum_{l=1}^{p} G_{jl} n_{jl} \quad (2)$$

and its boundary conditions as written in (3) to (5).

$$b_k = \sum_{j=1}^{s} m_{jk} n_j + \sum_{j=s+1}^{r} \sum_{l=1}^{p} m_{jk} n_{jl}, k = 1, \ldots, E \quad (3)$$

$$\sum_{i=1}^{r} n_i \Delta H_{f,feed,298,i}^0 \sum_{i=1}^{r} n_i H_i (T_{feed,i}) + Q_g = \sum_{i=1}^{r} n_i \Delta H_{f,prod,298,i}^0 \sum_{i=1}^{r} n_i H_i (T_{prod,i}) + Q_L \quad (4)$$

$$n_i \geq 0 \quad (5)$$

Where, ΔG_{min} is the change in Gibbs free energy, ni is the number of moles of each component, m is the matrix of each atom, s is a single-phase, r is the number of components, p is the number of phases, b is the number of moles of the element, E is the number of elements, Q_g is the heat of the gasification reaction and Q_L is the heat loss. The equations were then solved simultaneously using the ChemCad process simulator software. The simulation was prepared for the concept of combining RDF-pellet gasification with 100 kWe. The results from the observation of the impact parameters on the gas composition when RDF-pellets was gasified at an air ratio of 0.3-0.4 are needed for calculating of gasifier dimension.

2.3 RDF-Pellets Gasification in A Small Gasifier
The information on syngas quality and gasification efficiency is needed for designing a gasifier. RDF-pellets characteristics have to be determined prior to the design gasifier [7]. Syngas quality is influenced by RDF-pellets characteristics and process parameters. Process parameters such as air-fuel ratio and number of RDF-pellets have to be found as a parameter to determine gasifier dimensions. Experimental work has been conducted to find out one of the gasifier efficiency parameters that represented by specific gasification rate, SGR [8]:

$$\mathrm{SGR} = \frac{\mathrm{FCR}}{\mathrm{A_R}} \quad (6)$$

where FCR is RDF-pellets consumption rate, kg/hr. and A_R is a unit area of the gasifier m^2. The small stratified gasifier of 149 mm and 590 mm in diameter and height, respectively and RDF-pellet heat power input of 5 kW_{th} was used in this experiment. The gasifier is equipped with a 6 W blower and an ash removal chamber. A batch of was gasified to find out the by its RDF-pellets specific gasification rate.

2.4 Gasifier Design Consideration
Open top gasifier dimension (diameter and height) and superficial syngas velocity are the most influential parameters to RDF-pellets gasification. The dimension was based on the power output of the syngas engine. For this reason, the specifications of the engine must be determined as presented in Table 1.

TABLE 1
SPECIFICATION OF 100 KW DIESEL ENGINE

No.	Model	SD 100 (GENERAC)
	Type	Vertical, water cooling, four-stroke direct combustion chamber
1	Number of cylinders	6
2	Bore, mm (in)	104 (4.09)
3	Stroke, mm (in)	128 (5.2)
4	Compression ratio	16.5:1
5	Total displacement, L (cu In)	6.7 (406.86)
6	Firing order	1-2
7	Rated power, kW (rpm)	152 (2250)
8	Cooling method	Force water cooling
9	Minimum specific fuel consumption at full load, gal/h (L/hr.)	7.3 (27.6)

Base on the diesel engine specification, the maximum air, and syngas intake into the engine cylinder can be calculated by the below formula [9].

$$Q_g \frac{1/2 \times \mathrm{rpm} \times v_f}{60 \times 1000} \quad (7)$$

where Q_g gas intake, m^3/s; rpm is rate power, 2250 rev./min.; v_f is total displacement (volume), L. If the syngas RDF-pellet heating value, Hg, kJ/Nm^3 is obtained from the gasification simulation results, then the thermal power syngas, P_g, kW, and the maximum expected electrical output, P_E, kW can be obtained. By using the specific gasification rate, SGR obtained from the experimental results of RDF-pellets gasification in a small stratified gasifier (Eq. 6), the gasifier diameter, D_R, mm of the gasifier can be calculated using the following empirical formula [9].

$$D_R = \frac{(1130 \times G_m)}{q} \quad (8)$$

RDF-pellet consumption of gasifier, G_m, kg/s is calculated from the consumption of thermal power syngas (full load), P_g, kW divided by RDF pellets heating value, H_P, kJ/kg. thus, the gasifier reactor height, H, mm can be determined simply by using the following formula:

$$H = D_R + 1.5D_R \quad (9)$$

Quantitatively that the design of the gasifier is valid to be applied, it can theoretically be measured quantitatively as the ratio between the energetic syngas RDF-pellet heating value, H_g and the energy in the RDF-pellet, H_p fed in the gasifier and it is defined as follows [1], [9], [10]:

$$\eta_m = \frac{H_g \times Q_g}{H_p \times M_p} \times 100\% \qquad (10)$$

Mechanical efficiency of gasification, η_m, % is an index to evaluate the performance of RDF-pellets gasification, while M_p, kg/s is gasifier solid fuel consumption.

3 RESULT AND DISCUSSION

3.1 Physicochemical Properties of RDF-pellets

Three types of RDF-pellets were formulated by mixing organic waste and plastic waste in a small fraction with respect to their properties and heating values. The characteristic shape geometry of RDF-pellets for category A (100 % organic), category B (95% organic and 5% plastic) and category C (without sorting) are presented in Fig. 1.

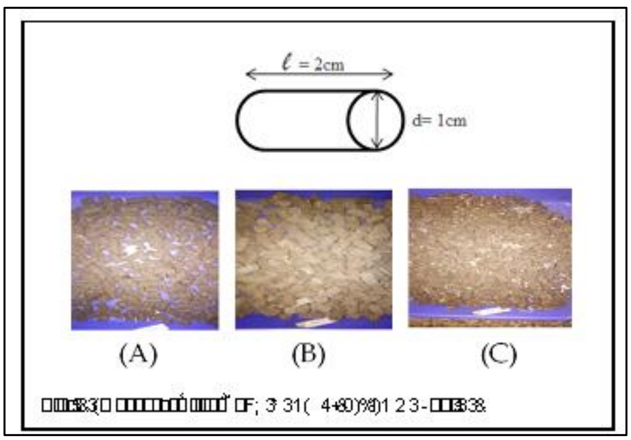

Fig. 1. *Chracteristic shape geometry of RDF-pellets*

Physicochemical properties (proximate and ultimate) and the heating values of RDF-pellets were analyzed to assess their thermal behavior. Table 2 shows the results of the proximate analysis and elemental analysis of the individual RDF type. The RDF-pellets are relatively homogeneous and uniform size and shape with low-level plastic content with a heating value of 8 MJ/kg to 13 MJ/kg. The lower heating value of 23.7 MJ/kg of RDF was formulated from several municipal waste components is reported by Lei et al. (2016) [11]. María et al. [12] reported that the heating values of brassica pellet, olive stone, wood pellet within the range of 13-15 MJ/kg. It can be said that these RDF-pellets with heating values are still suitable for the industrial heating (electric) application. The similar empirical formula derived from an elemental composition of this RDF-pellets is in agreement with the empirical biomass pellet formula reported by Lei et al. (2016) [11]. The heating value of this RDF-pellets is influenced by components and elements. The increase of heating value corresponds to the higher content of C and H, while the heating value will decrease due to O content. H content also influenced to the heating value of RDF-pellets due to the formation of water. Moisture and ash absorb some of the heat will decrease net heating values [13]. Thus, it is reasonable that RDF type A has the highest heating value due to the higher C and H content and the least ash content.

TABLE 2

PROXIMATE AND ULTIMATE ANALYSIS OF RDF PELLETS

Analysis	RDF-Pellets type		
Proximate (%-b)	A	B	C
Moisture in air dried	10.38	9.18	6.12
Ash	12.68	20.50	47.86
Volatile matter	48.84	52.0	37.54
Fixed Carbon	12.45	13.32	8.48
Ultimate (%-b)			
S	0.19	5.60	3.69
C	31.77	35.98	23.57
H	5.07	1.46	1.22
N	1.55	0.23	0.2
O	33.09	31,23	23,46
LHV (MJ/kg)	9.61* 13.07**	9.82* -	7.68* -
Empirical formula	$CH_{1.92}O_{0.78}$	$CH_{0.49}O_{0.65}$	$CH_{0.62}O_{0.75}$

* Dulong's formula calculation, **Calorimetric measurement

The morphology (geometry) of RDF-pellets in terms of size are determinant factors for ignition. Therefore, other physical properties of RDF-pellets were also evaluated in this study, as presented in Table 3. In this study, macroporosity was measured as the percentage of the volume of voids among the RDF-pellets in bulk to the overall fill volume. While the single volume of cylindrical RDF-pellets was measured and calculated as a number of pellets respect to the diameter and length of cylindrical [14]. The geometry measurement formula for cylindrical pellet volume is avowed as:

$$V_c = \frac{\pi}{4} d^2 \sum l_i \qquad (11)$$

Where V_c is a volume of the cylindrical pellets, m^3, d is mean diameter, m, li is the variable length, m of i_{th} pellet, and n is the number of pellets use in the throng. While, the macroporosity, ϕ_c asserted from the fill volume, V_f and cylindrical pellet volume in percentage as:

$$\phi_c = \frac{V_f - V_c}{V_f} \times 100 \qquad (12)$$

In this experiment, it was found that of the ignition time of the RDF-pellet in the range of 1.5-3.0 s (with the addition of small amount alcohol droplets) and within around 300-100 s (without the addition of alcohol droplets). It was seen that the larger particle density and porosity and the presence of plastic content in RDF-pellets type B exhibited the greater ignition temperatures. It was understood, and increasing in the porosity of RDF-pellets, causing easier diffusion of air into particles while better combustion occurs.

TABLE 3

CYLINDRICAL RDF PELLETS DENSITY, POROSITY AND IGNITION

Type	Density, kg/m^3		Macro Porosity	Ignition, ℃
	Particle	Bulk		
A	717	471	34.97	297
B	1153	583	51.99	405

C	682	504	39.71	320

In the description above, it is clear that physicochemical properties affect the heating value of RDF-pellets. Therefore, it is reasonable that the heating value of the RDF-pellets is used as one of the parameters to calculate the gasifier dimensions of the next step as representing other properties.

3.2 Syngas Properties from RDF-Pellet Gasification

Number Several factors affect the quality syngas include RDF-pellet, gasifier type and operational conditions (air oxidizing agent, temperature and pressure). Due to the unavailability of experimental data, the model that was described in the previous section was intended to get the syngas properties. The simulation results were compared to experimental data reported in kinds of literature. The process modeling was conducted by the commercial software ChemCad 5.2 Process Simulation (Chemstations Inc). The describe gasification process of an RDF-pellets in a fixed bed downdraft gasifier is presented in Fig. 2, in accordance with the flowchart ChamCad. The elemental composition of the RDF-pellet as presented in Table 2 was provided in the modeling. The simulating gasification process of RDF-pellet was testing the sensitivity of the model predictions syngas compositions and heating value by varying air flowrate as the gasification medium. A constant RDF-pellet feed rate of 113.30 kg/hr. with a heating value of 13.85 MJ/kg was used to meet 100 kWe of electricity production. The airflow rates vary from 100 kg/hr. to 200 kg/hr. which in turn affects the temperature of the gasification. The amount of heat loss was set at 35% of the heating value of RDF-pellets. Since CO and H_2 are the major components and CO_2 also has a high concentration in the syngas, the following results present in Fig. 3.

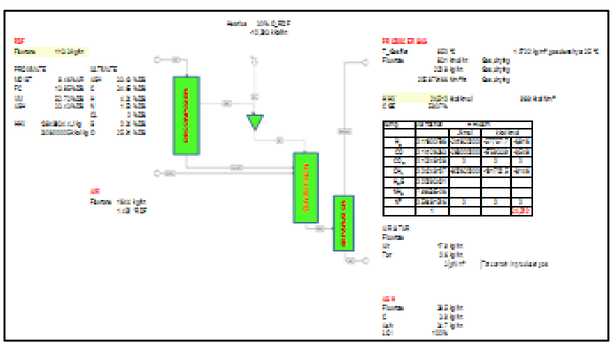

***Fig. 2**. Simulation sheet for the gasification of RDF-pellet*

The composition of the syngas depends mainly on the characteristics of RDF-pellets as well as on the conditions of the gasification process. The component fraction of syngas (CO, H_2, and CO_2) in syngas determines the quality of syngas, which affects the magnitude of the heating value of syngas and gasification efficiency. Fig. 3 shows the effect of air flowrate on the mole fractions of syngas. The higher amount of airflow rate, the increases of the mole fractions of the noncombustible components and decrease lower the mole fractions of the combustible gases [15], [16]. It indicates that a high amount of air introduces to gasifier which causes some combustible gas to burn.

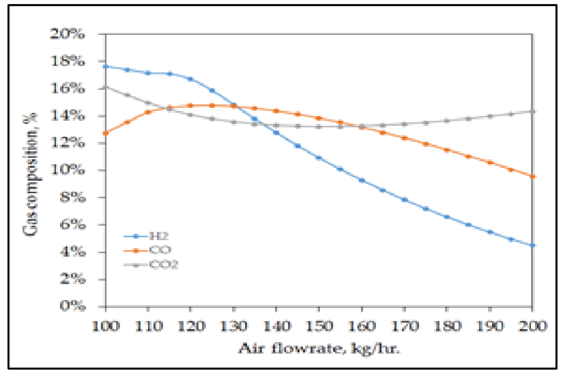

***Fig. 3**. Syngas composition vs air flowrate*

The composition of syngas of H_2: 11%, CO: 14%, CO_2: 13%, CH_4:4% N_2: 56% and the rest is NH_3 with net heating value 4070 kJ/Nm^3 was attained at temperature of 850 ^oC, airflow rate of 164.44 kg/hr. and gasification efficiency of 59.37%. The prediction of the model results in good agreement with the results obtained experimentally from other researchers [17]. Prando et al. (2016) [17]. reported the syngas composition with air oxidant of H_2: 9-10%, CO: 12-15%, CO_2: 14-17%, CH_4: 2-4, N_2: 56% with net heating value of 3-6 MJ/Nm^3 was measured from biomass gasification using an open-top gasifier. The higher composition of combustible gas and the heating values in the range of 7-20 MJ/kg was obtained by utilized different gasifying agent [10], [17]. These results are also similar and in agreement with previous experiments or simulations results of RDF/biomass gasification at about 800 ^oC and equivalent ratio, Φ (air to fuel ratio compare to stochiometric condition) of 0.2-0.3 [15], [16]. The net heating value of syngas of 4070 kJ/Nm^3 from this simulation results will be used to one of the parameters to design the gasifier in the next step. Although syngas actually contains some undesirable compounds such as tar that need to be removed to ensure acceptable diesel-engine operation. The tar content in syngas, although in very small quantity, is one of the main technological barriers to the use of gasification systems for engines application [18], [19].

3.3 The Specific Gasification Rate (SGR) of the RDF-Pellets

The SGR of the RDF-pellets as described referring to (6) depends on the size of the gasifier in terms of the diameter of the cross-section of the gasifier where the RDF is being gasified. The amount of fuel consumed per unit time, FCR must be measured first to find out SGR value.

***Fig. 4**. Small updraft RDF-pellet gasifier*

amount of 0.5 and 2.0 kg, respectively was gasified in a small updraft gasifier with the inner diameter and height gasifier was 14.5 cm and 59 cm, respectively and assembled with one 6 W blower for supplying air, as depicted on Fig. 4. The amount of air introduced to the gasifier during the gasification of RDF-pellets was measured using a digital anemometer Krisbow-KW06-653. It was found out that the gasification occurs at air inlet lower from the stoichiometric needs. The average material consumption rate of RDF-pellets in this small gasifier is 1.79 kg/hr. The SGR of RDF-pellets from an experiment using the small updraft gasifier was summarized in Table 4. The specific gasification rate of the RDF-pellets from this experiment ranging from 58 to 202 kg/m^2.hr. with an average SGR of 112 kg/m^2.hr. As a comparison, the specific gasification rate of solid biomass is in the range 50-250 kg/m^2.hr. [20], [21], [22]. It was observed that the specific gasification rate of RDF was affected by the equivalence ratio, Φ. The higher of the equivalence ratio, Φ signifies the higher of air flowrate for an SGR of RDF-pellets. With the increase of the equivalence ratio, Φ, the SGR of RDF-pellets continuously increases. An increase in the equivalence ratio, Φ indicates that more oxygen was provided for the RDF-pellets oxidation and a higher of combusted RDF-pellets. The higher energy release will enhance the drying and pyrolysis rate. The higher number of RDF-pellets would also intensify the combustion rate. Therefore, the fuel consumed rate, FCR of RDF-pellets not only due to higher combustion rate but enhanced pyrolysis and drying rate as well [21]. So, it can be said, that increasing the number of RDF-pellets and the higher equivalent ratio, Φ conduce an increasing in SGR of RDF-pellets, as summarized in Table 4. Thus, very reasonable that the SGR values from the results of this experiment are feasible to be used as a parameter for designing a 100kWe scale downdraft open top gasifier.

TABLE 4
THE SGR OF RDF-PELLETS

Type	Weight, kg	Operation time, hr.	SGR, kg/m^2.hr.	Equivalent ratio, Φ
A	0.5	0.28	107	
	2.0	0.60	202	
B	0.5	0.51	58	
	2.0	1.58	77	
C	0.5	0.30	100	0.2-0.35
	2.0	0.93	130	
Average	1.25	0.70	112.33	

3.4 The Calculation of the Gasifier Dimensions

The calculation was intended for the downdraft open top gasifier which uses RDF-pellets as gasification feedstock. The purposeful of design consideration parameters was the power output was about 100 kWe for SD 100 GENERAC diesel engine. Based on engine specifications of rate power and total displacement 2250 rpm and 6.7 L, the maximum air and syngas intake into the engine cylinder was calculated using (7) was 0.1256 m^3/s. In general, the ratio of air to syngas is 1:1. 225. For a well-designed and clean air inlet manifold, the efficiency is usually around 80% [9]. So that, the real syngas intake, Qg would be 0.0553 m^3/s. The net heating value of syngas, Hg 4070 kJ/Nm^3 from above RDF-pellet gasification simulation result was taken to calculate the thermal power in the gas as follow:

$$Pg = 0.0553 \times 4070 = 225.20 \text{ kW} \quad (13)$$

Therefore, the maximum, P_E mechanical power output of this engine using the efficiency of 52.5% for a compression ratio of 16.5: 1 was 118. 23kW = 158.45 HP. Commonly, the efficiency of the generator in the range of 80-90%. The efficiency of 85% was taken to calculate the maximum electrical power output;

$$P_{E,\ max.} = 118.23\times\ 0.85 = 100.45 \approx 100 \text{ kWe} \quad (14)$$

The gasification efficiency of 59.37% from the simulation result was used to estimate thermal power consumption (full load). In this case, the lower gasification efficiency of 50.0% was chosen for the thermal power consumption for the full load and it was found 450. 398 kW.

The heating value of RDF pellet (8,36% -10,38% MC): 13079 kJ/kg from proximate and ultimate analysis (Table 2) was taken into account for RDF pellet consumption of gasifier:

$$G_m = \frac{450{,}398 \frac{kJ}{s}}{13079 \frac{kj}{kg}} = 0.03443 \frac{kg}{s} = 123.97 \frac{kg}{hr.} \quad (15)$$

It is meant for 100 kWe installation consideration uses:

$$\frac{G_m}{P_{E,max}} = \frac{123.97}{100.45} = 1.23 \frac{kg}{kWh} \quad (16)$$

from this Eq. (16) it can be stated that to produce electricity 1 kWh is needed 1.23 kg RDF-pellets. The SGR of RDF-pellets from an experiment using the small updraft gasifier (Table 3) was used to find out the diameter and height of the gasifier. For the appropriateness of the design, the SGR of RDF-pellets of 100 kg/m^2.hr and 200 kg/m^2.hr. were chosen to calculate the gasifier dimensions using (8) and (9). The diameter and height of the gasifier reactor are in the range of 0.7~1.4 meter and 1.8~3.5 meter, respectivelyThe gasification efficiency, η_m depends upon the type and design of the gasifier as well as on the characteristics of RDF-pellets. The η_m from simulation result on the above descript condition was 59.37%. A minimum value was obtained for the gasification efficiency, η_m of 100 kWe the open-top gasifier design which is calculated using (10) by 50%.

4 CONCLUSION

On the mechanical output power basis of diesel engine specifications, experimental and simulation data the gasifier diameter and height of downdraft open top gasifier were found in the range of 0.7-1.4 meter and 1.8-3.5 meter, respectively. The design of the gasifier reactor with this dimension is expected to be installed with a diesel engine for applications in small industries or other purposes. The minimum 123 kg RDF-pellets is needed to gain the thermal power of the syngas of 225,20 kW in producing electricity of 100 kWe.

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