

Analysis of Product and Temperature of Biogas Combustion in Various Air Biogas Equivalence Ratio and Methane Content

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Received April 12, 2017; Accepted March 2, 2018

ABSTRACT

Biogas resulted from anaerobic digestion of organic compounds have various methane content depend on the type of the degraded material. The methane content of biogas is range between 40–80% that influence the heating value and combustion characteristic of that biogas. The higher methane content can be obtained through upgrading biogas by removing CO₂ and other trace components like H₂S, NH₃, and water vapor. This research was a simulation of product composition and temperature of biogas combustion in various methane content and air biogas equivalence ratio. Biogas combustion was done in combustion chamber at constant pressure of 1 atm. Biogas and air enter into combustion chamber at temperature approximately of 30 °C as the common ambient temperature in Indonesia. The input air was designed higher than stoichiometric need in order to reach complete combustion. Combustion reaction between methane and O₂ then carried out in the combustion chamber to produce CO₂ and H₂O. The product gases consisting of CO₂, H₂O, N₂, and excess O₂, bring heat from combustion reaction and exit from combustion chamber at the higher temperature. The analysis was done for methane content range between 20 and 100% with air biogas equivalence ratio from 1 until 3. The simulation result showed that for V m³ biogas, the combustion gases could reach 0.12271 until 1.26798V gmol with temperature above 700 °C until above 1900 °C. More than 50% component in the combustion gases is N₂ as inert material from input air to combustion chamber.

Keywords: product; temperature; biogas combustion; methane

ABSTRAK

Biogas yang dihasilkan dari peruraian berbagai macam senyawa organik memiliki kadar metana yang berbeda-beda tergantung jenis senyawa organik yang diuraikan. Kadar metana dalam biogas bervariasi antara 40–80%, sehingga mempengaruhi nilai panas dan karakteristik dari biogas tersebut. Kadar metana yang lebih tinggi dapat dicapai melalui pemurnian biogas dengan menghilangkan CO₂ dan komponen-komponen kecil dalam biogas seperti H₂S, NH₃, dan uap air. Penelitian ini adalah simulasi terhadap komposisi produk dan suhu pembakaran biogas pada berbagai kadar metana dan perbandingan equivalen udara-biogas. Pembakaran biogas terjadi di ruang bakar pada tekanan konstan 1 atm. Biogas dan udara memasuki ruang bakar pada temperatur 30 °C, temperatur udara pada umumnya di Indonesia. Kuantitas udara pembakaran dirancang di atas kebutuhan stoikiometris untuk memperoleh pembakaran yang sempurna. Reaksi pembakaran kemudian terjadi di ruang bakar antara metana dan O₂ menghasilkan CO₂ dan H₂O. Gas hasil pembakaran mengandung CO₂, H₂O, N₂ inert, dan kelebihan O₂, membawa panas yang dihasilkan dari reaksi pembakaran dan keluar dari ruang bakar dengan temperatur yang lebih tinggi. Analisis dilakukan pada kadar metana antara 20 dan 100%, dan pada perbandingan equivalen udara-biogas antara 1 dan 3. Hasil simulasi menunjukkan bahwa untuk V m³ biogas, jumlah gas hasil pembakaran dapat mencapai 0,12271 sampai 1,26798V gmol dengan suhu di atas 700 °C sampai di atas 1900 °C. Lebih dari 50% komponen di dalam gas hasil pembakaran adalah N₂ sebagai gas inert yang terbawa bersama udara pembakaran.

Kata Kunci: produk; suhu; pembakaran biogas; metana

INTRODUCTION

The effort to save fossil fuels energy source in Indonesia is done continuously and seriously in some recent years through the development of research and application of renewable energy source, including

biogas. The utilizations of cow manure as raw material for biogas production have been implemented in some small scale ranch, and the utilizations of human feces have been implemented in some area with concentrated population such as in boarding school, to produce biogas for electricity power generation. The

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others organic resources like sea weeds and organic waste like fruit and municipal solid waste also potentially to be used as raw material in biogas production. The capture of CH₄ and CO₂ emissions through anaerobic digestion of organic materials in biogas production is a simple and applicable process to solve the greenhouse effect and produce energy in the same time. The combustion process of biogas is also environmentally friendly because it produce more H₂O than CO₂ [1]. The heating value is significantly, can reach 20–26 MJ/m³ [2]. Compared with other source of renewable energy, biogas is considered as excellent [2] and environmentally friendly energy source, clean, and manageable [3].

Biogas resulted from anaerobic digestion of organic materials [1,4] have various methane content depend on the type of raw material to be degraded and also the degradation condition in the digester, i.e. temperature and retention time [5]. The estimation of methane content from the degradation of protein is about 63% [6], from the degradation of fat is about 70% [6], and from the degradation of cellulose is about 50% [6]. The methane content of gas produced from sanitary landfill can reach 45–55% [7], or 45–65% [8], lower than the methane content of biogas from anaerobic digestion process, caused by the possibility the present of air in semi-aerobic sanitary landfill degradation process, the aerobic process then dramatically decrease CH₄ production [9] and methane content of biogas. Free-H₂S biogas can reach methane content more than 80% [10]. The higher methane content can be obtained through upgrading biogas by removing CO₂ [1] and other trace component such as H₂S, NH₃, and water vapor. According to Karapidakis et al. [11], it possible to reach the methane content to nearly 100%.

The variation of methane content in biogas will influence the heating value and combustion characteristics of that biogas. The temperature of combustion product gases is an important parameter to investigate the thermal phenomena in biogas combustion [3]. The temperature and composition of combustion product gases are also important parameters in equipment design of biogas system. Previous researches had studied the combustion characteristic of biogas, many researchers studied the combustion performance of biogas in internal combustion SI and CI engine [8,12-20], the characteristics in microgas turbine [21-23] and also specifically on the characteristics in biogas burner [5,24-30]. Largely, the previous researches of combustion in biogas burner were done in a certain methane content of biogas, i.e. 40% [29], 51% [31], 60% [5,27-29], 61% [29-30], and also 100% [29]. The burners used were burner for gas turbine configuration [30], MILD or flameless burner [28], and lab scale furnace [27]. The thermal and

chemical characteristics of conventional counter flow diffusion flame of biogas for methane content 100, 60, 61 and 40% have been studied [29]. Numerical study of oxygen dilution and temperature distribution of biogas combustion was studied by Noor et al. in MILD burner [28]. Dahiya et al. predict the composition and temperature of combustion product of biogas by considering the dissociation reaction of the product and component gases in the combustion process, and validated with experimental measurements [5]. For non-seeded biogas the study limited in the stoichiometric condition and for the product composition it was limited for methane content 60% and CO₂ 40% [5]. Caine present the theoretical temperature of biogas combustion using air as much as 100–200% of stoichiometric need, in various level of methane [26], however the methods to obtain the value of the temperatures were not explained and the product composition as a function of methane content and excess air was not presented. Considering that biogas from various type of substrate have various level of methane, the need of excess air to reach complete combustion, and besides the combustion temperature, the composition of combustion product gases is an important parameter in biogas equipment design, this research will analytically study the combustion characteristic of biogas through simulation of product and temperature that can be achieved in various level of methane from 20 to 100% and air biogas equivalence ratio from 1 to 3. The combustion characteristics are investigated at constant pressure, and the results of the simulation are then compared with previous researches from literature.

EXPERIMENTAL SECTION

The system will be discussed in this study is biogas burner, the place where the combustion reaction between CH₄ in the biogas and O₂ from the air carried out. To determine the product composition and the temperature that can be achieved, it is needed to understand the scheme of the process and the combustion reaction that happen between biogas and air. In the simulation, the reaction is assumed as complete combustion, therefore, the products are CO₂ and H₂O only. There are also present others gases, i.e. N₂, CO₂ from biogas, and excess O₂ that did not involve in the combustion reaction but present in the output gases stream from combustion chamber. In practice, those gases can be analyzed using gas analyzer or gas chromatography with certain detector. All of those gases are then called as combustion product gases, this gases bring heat that was produced from combustion reaction in the form of sensible heat and have higher temperature than the input gases stream.

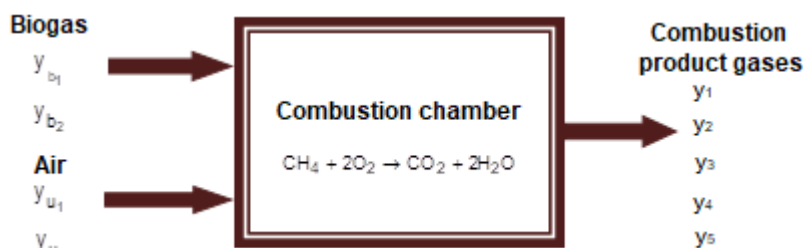


Fig 1. The scheme of biogas combustion process

CH ₄ + 2O ₂ → CO ₂ + 2H ₂ O					
	CH ₄ , gmol	O ₂ , gmol	CO ₂ , gmol	H ₂ O, gmol	N ₂ , gmol
Feed	y _{b₁} ·n _b	λ(2y _{b₁} ·n _b)	y _{b₂} ·n _b	-	$\frac{y_{u_2}}{y_{u_1}} \left\{ \lambda (2y_{b_1} \cdot n_b) \right\}$
Reaction	y _{b₁} ·n _b	2y _{b₁} ·n _b	y _{b₁} ·n _b	2y _{b₁} ·n _b	-
Product	-	(λ-1)(2y _{b₁} ·n _b)	(y _{b₂} + y _{b₁})n _b	2y _{b₁} ·n _b	$\frac{y_{u_2}}{y_{u_1}} \left\{ \lambda (2y_{b_1} \cdot n_b) \right\}$

Fig 2. Calculation scheme of input and output gases

The scheme of combustion process in combustion chamber is presented in Fig. 1.

CH₄ and CO₂ are the main component that present in biogas [7,32], other components like H₂S, H₂O, and NH₃ exist in relative small amount [33], therefore, in this simulation, it is assumed that biogas only contain of CH₄ and CO₂. The methane content in biogas is expressed by C_{b₁} (% volume), CO₂ content in biogas is expressed by C_{b₂} (% volume), mole fraction of methane in biogas expressed by y_{b₁}, and mole fraction of CO₂ in biogas is expressed by y_{b₂}. The value of y_{b₁} and y_{b₂} can be calculated using eq. 1 and 2 as follow:

$$y_{b_1} = \left(\frac{C_{b_1}}{C_{b_1} + C_{b_2}} \right) \quad (1)$$

$$y_{b_2} = \left(\frac{C_{b_2}}{C_{b_1} + C_{b_2}} \right) \quad (2)$$

To oxidize CH₄ in biogas, it is used atmospheric air that assumed contain of O₂ as much as 20% and N₂ as much as 80%. Mole fraction of oxygen in the air is expressed by y_{u₁} and mole fraction of nitrogen in the air is expressed by y_{u₂}. The combustion reaction is happen in the combustion chamber between CH₄ in the biogas and O₂ from the air:



The combustion product gases consist of CO₂ and H₂O produced from the reaction and other gases that not involved in the combustion reaction i.e. CO₂ from input biogas to combustion chamber, N₂ inert and excess O₂ from input air to combustion chamber. Mole fraction of

CH₄, O₂, CO₂, H₂O, and N₂ in the combustion gases are then expressed by y₁, y₂, y₃, y₄, and y₅ respectively. For the combustion of V_b m³ biogas, the moles amount of this biogas can be calculated using ideal gas equation, as follow:

$$n_b = \frac{PV_b}{RT_i} \quad (4)$$

in which n_b is moles of biogas (gmol), P is pressure (atm), R is ideal gas constant (L.atm/gmol.K), and T_i is temperature of input gases to combustion chamber (K). In order to reach complete combustion, it is needed to design input oxygen higher than stoichiometric need. The air biogas equivalence ratio is defined as the ratio of actual air biogas ratio to the stoichiometric air biogas ratio. If the air biogas equivalence ratio is λ, the amount of input air and products of the combustion reaction can be estimated based on the stoichiometric reaction of biogas combustion as presented in the scheme in Fig. 2.

Amount of CH₄, O₂, CO₂, H₂O and N₂ in the input gases can be calculated using eq. 5, 6, 7, 8, and 9, as follow:

$$n_{i_1} = y_{b_1} \cdot n_b \quad (5)$$

$$n_{i_2} = \lambda (2y_{b_1} \cdot n_b) \quad (6)$$

$$n_{i_3} = y_{b_2} \cdot n_b \quad (7)$$

$$n_{i_4} = 0 \quad (8)$$

$$n_{i_5} = \frac{y_{u_2}}{y_{u_1}} \left\{ \lambda (2y_{b_1} \cdot n_b) \right\} \quad (9)$$

with n_{i₁}, n_{i₂}, n_{i₃}, n_{i₄}, and n_{i₅} respectively is moles of CH₄, O₂, CO₂, H₂O, and N₂ in the input gases stream (gmol). It is assumed that no H₂O presence in the biogas

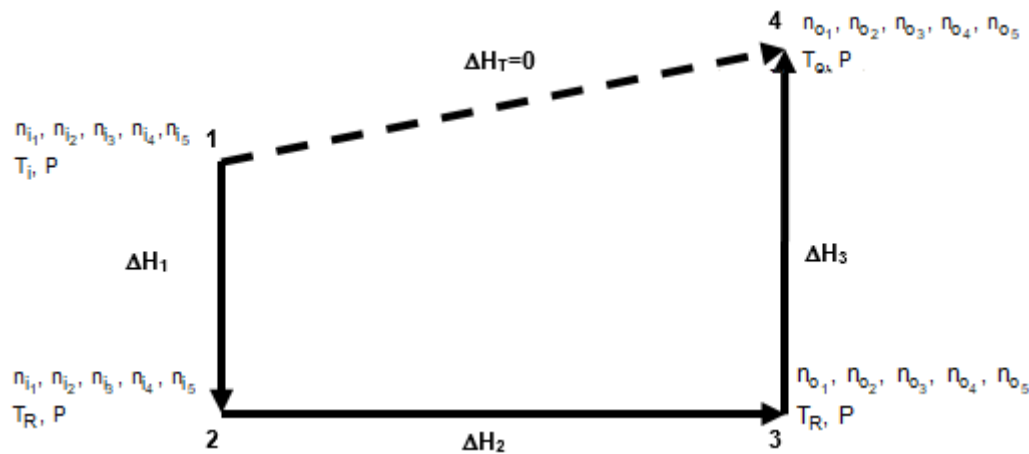


Fig 3. The enthalpy change in biogas combustion process

and combustion air, so that the value of n_{i_4} is zero. Total moles of input gases into combustion chamber (n_{i_t} , gmol) can be calculated by summing moles of each component. Because biogas only consist of CH_4 and CO_2 , the value of $y_{b_1} + y_{b_2} = 1$. Total amount of input gases can be calculated as follow:

$$n_{i_t} = n_b + \lambda(2y_{b_1} \cdot n_b) + \frac{y_{u_2}}{y_{u_1}} \left\{ \lambda(2y_{b_1} \cdot n_b) \right\} \quad (10)$$

with n_{i_t} is total moles of input gases into combustion chamber (gmol).

Based on the scheme in Fig. 2, moles of CH_4 , O_2 , CO_2 , H_2O and N_2 in the combustion product gases can be calculated as follow:

$$n_{o_1} = 0 \quad (11)$$

$$n_{o_2} = (\lambda - 1)(2y_{b_1} \cdot n_b) \quad (12)$$

$$n_{o_3} = n_b \quad (13)$$

$$n_{o_4} = 2y_{b_1} \cdot n_b \quad (14)$$

$$n_{o_5} = \frac{y_{u_2}}{y_{u_1}} \left\{ \lambda(2y_{b_1} \cdot n_b) \right\} \quad (15)$$

with n_{o_1} , n_{o_2} , n_{o_3} , n_{o_4} , and n_{o_5} respectively is moles of CH_4 , O_2 , CO_2 , H_2O , and N_2 in the combustion product gases (gmol). Total moles of output gases from combustion chamber is the summation of moles of each component in the combustion product gases, be calculated as follow:

$$n_{o_t} = n_b + \lambda(2y_{b_1} \cdot n_b) + \frac{y_{u_2}}{y_{u_1}} \left\{ \lambda(2y_{b_1} \cdot n_b) \right\} \quad (16)$$

with n_{o_t} is total combustion gases (gmol).

Calculation of maximum temperature in this research was done based on common method to calculate combustion product temperature that also

explained by [34-35]. The actual combustion process goes from the initial condition when the biogas and air enter to combustion chamber at temperature T_i (K) to products at temperature T_o (K) [34]. However, to ease the calculation, the maximum temperature of combustion gases was calculated based on the alternative process path in Fig. 3, from reactants at temperature T_i (K) that are initially cooled to standard temperature (T_R) of 298 K, the combustion reaction is then carried out at a constant temperature of 298 K, the product of combustion are then heated from 298 K to the final temperature of T_o (K) [34]. The kinetic and potential energy changes are negligible and no work is done, so that the overall energy balance reduces to $\Delta H_T = 0$ [35].

ΔH_1 (Joule) is the enthalpy change of reactants as they are cooled from T_i to T_R , can be written as:

$$\Delta H_1 = \int_{T_i}^{T_R} (n_{i_1} \cdot C_{p_1} + n_{i_2} \cdot C_{p_2} + n_{i_3} \cdot C_{p_3} + n_{i_4} \cdot C_{p_4} + n_{i_5} \cdot C_{p_5}) \cdot dT \quad (17)$$

with C_{p_1} , C_{p_2} , C_{p_3} , C_{p_4} , and C_{p_5} respectively is heat capacity of CH_4 , O_2 , CO_2 , H_2O , and N_2 (J/gmol.K).

ΔH_2 (Joule) is heat released from the combustion of methane in biogas, can be calculated as follow:

$$\Delta H_2 = n_{i_1} \cdot \Delta H_c \quad (18)$$

with ΔH_c is the standard heat of combustion of methane (802620 J/gmol in temperature of 298, 15 K [36]).

ΔH_3 (Joule) is the enthalpy change of products as they are heated from T_R to T_o , can be calculated as follow:

$$\Delta H_3 = \int_{T_R}^{T_o} (n_{o_1} \cdot C_{p_1} + n_{o_2} \cdot C_{p_2} + n_{o_3} \cdot C_{p_3} + n_{o_4} \cdot C_{p_4} + n_{o_5} \cdot C_{p_5}) \cdot dT \quad (19)$$

ΔH_T (Joule) as the actual enthalpy change of the combustion process is the summation of ΔH_1 , ΔH_2 , and ΔH_3 . The maximum temperature will be achieved when no heat loss from the system and all of combustion

heat is used to increase temperature of product gases, therefore with assumption that the system is adiabatic, the value of $\Delta H_T = 0$, can be written as follow:

$$\Delta H_T = \Delta H_1 + \Delta H_2 + \Delta H_3 = 0 \quad (20)$$

The maximum temperature of the combustion product gases (T_o) can be calculated by substituting the value of ΔH_1 , ΔH_2 , and ΔH_3 in eq. 20 with the value of ΔH_1 , ΔH_2 , and ΔH_3 from eq. 17, 18, and 19, and trying the value of T_o until it is obtained the summation of ΔH_1 , ΔH_2 , and ΔH_3 in eq. 20 approximately to zero.

RESULT AND DISCUSSION

The calculation of combustion product and maximum temperature of biogas combustion were done based on the amount of input biogas to combustion chamber as much as $V \text{ m}^3$, the temperature of input biogas and air into combustion chamber were assumed about $30 \text{ }^\circ\text{C}$, as the common ambient temperature in Indonesia. The combustion was carried out at constant pressure of 1 atm. The data of C_p for each component that present in the combustion chamber were obtained from Smith et al. [35]. Based on the design variables mentioned above, the maximum temperatures of

combustion product gases were calculated by solve eq. 1–20 simultaneously. The simulation was done in the possibly range of methane content for biogas from 20 to 100% and air biogas equivalence ratio from 1 to 3.

Product Gases Composition

The composition of combustion product gases is influenced by the composition of input gases and the combustion reaction that occur between methane in biogas and O_2 from combustion air. Furthermore, the composition of input gases is influenced by the present of inert component and the excess of air in the combustion chamber or influenced by the methane content of biogas and air biogas equivalence ratio. Figure 4 show the calculation result of product gases from biogas combustion based on eq. 1–15.

Fig. 4a show that moles of CO_2 in the combustion product gases show the same values in various level of methane and air biogas equivalence ratio. It happen because CO_2 in the input gases is derived only from biogas and not from combustion air, therefore, component CO_2 in the product gases is derived from CO_2 in the input biogas and CO_2 produced from combustion reaction of methane in biogas.

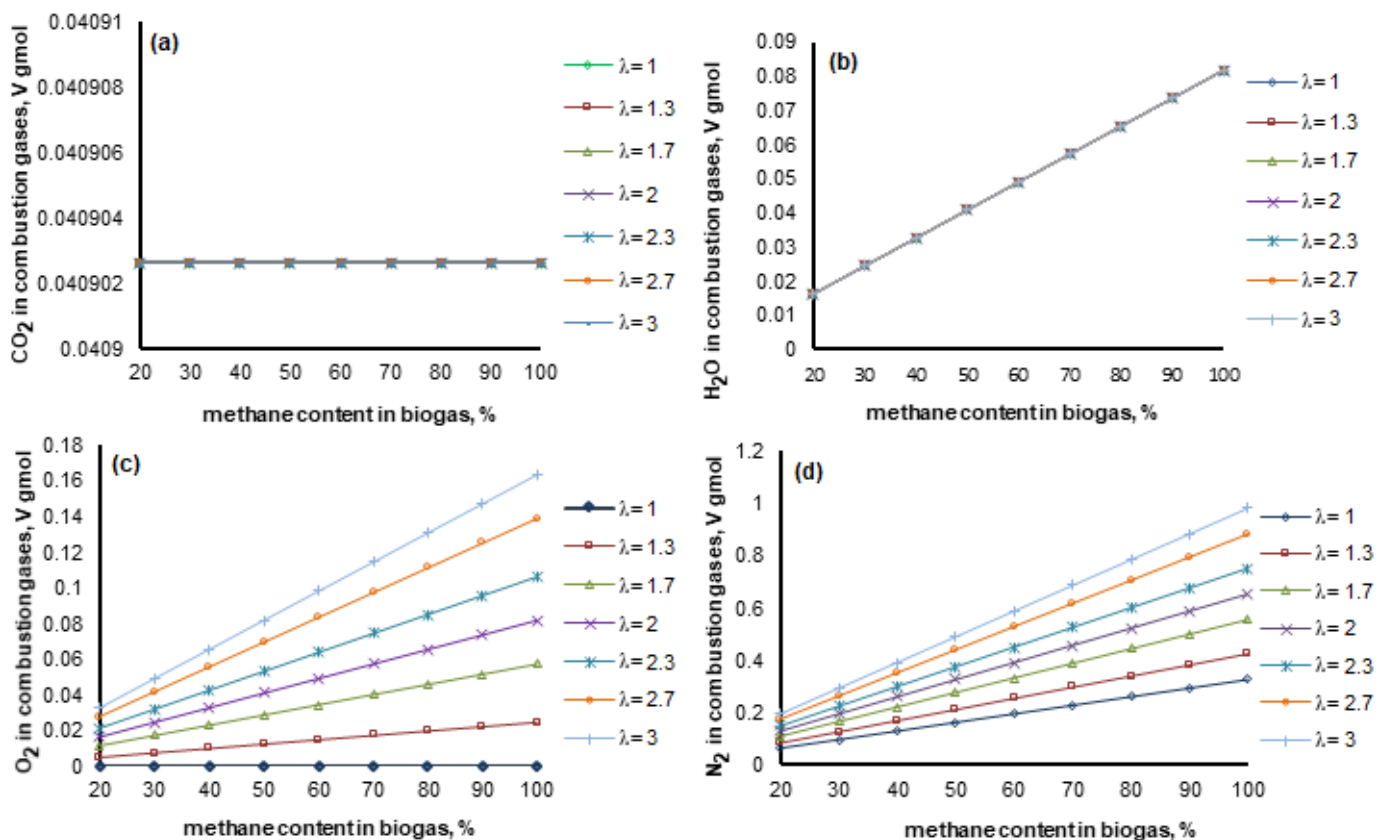


Fig 4. Composition of biogas combustion product (a) CO_2 , (b) H_2O , (c) O_2 , and (d) N_2

Since the reaction was assumed as complete combustion in all air biogas equivalence ratio, all of methane in biogas will be combusted to produce CO_2 and H_2O . From eq. 3 it can be seen that the combustion reaction of methane will produce CO_2 with same moles with CH_4 involved in the reaction, therefore, because in the calculation it was assumed that biogas only consist of CH_4 and CO_2 , moles CO_2 in the combustion product gases as the summation of moles CO_2 from input biogas and moles CO_2 produced from the combustion reaction will be same with the total moles of CO_2 and CH_4 in the input biogas and also same with total moles of input biogas to combustion chamber. Due all the calculation was done based on $V \text{ m}^3$ biogas (0.0409V g/mol), moles of CO_2 in the product gases will also 0.0409V g/mol in various methane content and air biogas equivalence ratio.

Fig. 4b show that moles of H_2O in the product gases in various air biogas equivalent ratio is same when the combusted biogas have same methane content. It happen because H_2O was not existed in the input biogas and also not existed in the input air and only produced from the combustion reaction of methane in biogas, therefore the amount of H_2O in the combustion product gases will depend on the amount of methane in biogas. When the methane content of biogas is same, although the air biogas equivalent ratio is different, based on the same volume of biogas to be combusted, the product H_2O from complete combustion will also be same.

In the higher methane content, the amount of methane to be combusted is higher so that the amount of H_2O produced from the reaction will also be higher, that imply in the higher amount of H_2O in the combustion product gases. H_2O present in the combustion product gases from about 0.01636V g/mol when the methane content 20% up to about 0.08181V g/mol when the methane content of biogas is 100% (pure methane).

Fig. 4c and 4d show that moles of O_2 and N_2 in the combustion gases tend to increase with the increasing of air biogas equivalence ratio and also with the increasing of methane content in biogas. Because O_2 and N_2 were the main component in the combustion air, when the air biogas equivalence ratio is higher and the methane content is same, the amount of input air into combustion chamber will be higher that mean the higher input O_2 and N_2 . In the same methane content, the amount of O_2 reacted will be same, when the air input is higher, the excess O_2 that involved in the combustion gases will also be higher (Fig. 4c). For N_2 , the higher air biogas equivalence ratio means the higher input air and also the higher input N_2 . Because N_2 is an inert component, the higher N_2 in the input air will imply in the higher N_2 in the combustion product gases (Fig. 4d).

In the same air biogas equivalence ratio, the amount of O_2 and N_2 in the combustion gases is tends to increase with the increasing of methane content in biogas. When the methane content is higher, the amount of methane in biogas is higher too, it imply in the higher input air to be fed in to combustion chamber, as well as O_2 and N_2 . Furthermore, the amount of N_2 in the combustion gases as inert component in the combustion process will also be higher (Fig. 4d). N_2 in the combustion gases calculated as much as 0.06544V g/mol in methane content 20% and air biogas equivalence ratio 1, and, 0.98166V g/mol when the methane content 100% and air biogas equivalence ratio 3.

For O_2 , although some O_2 in combustion air will involve in the combustion reaction, when the methane content is higher, the excess O_2 in certain air biogas equivalence ratio will also be higher (Fig. 4c). The amount of O_2 that involved in the combustion reaction will be equivalence with methane content of biogas, and, in the same air biogas equivalence ratio, the excess O_2 will also be equivalence with the methane content of biogas. There were no excess O_2 in the combustion gases when the air biogas equivalence ratio is 1 because all input O_2 from combustion air involved in the combustion reaction. Excess O_2 can reach 0.03272V g/mol when the air biogas equivalence ratio is 3 and the methane content is 100%.

Totally, all of the calculation showed that the main component present in the biogas combustion product are CO_2 , H_2O , O_2 , and N_2 . N_2 as an inert component, present in high amount, more than 50%. Fig. 4 show that N_2 present in combustion gases from about 0.0654V g/mol to about 0.98166V g/mol, significant higher than CO_2 as much as 0.04090V g/mol, also significant higher than H_2O from about 0.01636V g/mol to 0.08181V g/mol, and also than O_2 from 0 g/mol to 0.03272V g/mol. In the actual combustion process, the combustion gases may also contain CO as a result of uncompleted combustion [26], some unburned methane, and NO_x as a result of N_2 oxidation in high combustion temperature [26].

Maximum Temperature of Product Gases

The maximum temperature of combustion gases is influenced by the composition and temperature of input gases, combustion reaction temperature, composition of combustion product gases and the heating value of biogas. Fig. 5 shows the correlation of those parameters with methane content of biogas when the air biogas equivalence ratio was 1.3 (Fig. 5a) and with air biogas equivalence ratio when the methane content of biogas was 50% (Fig. 5b).

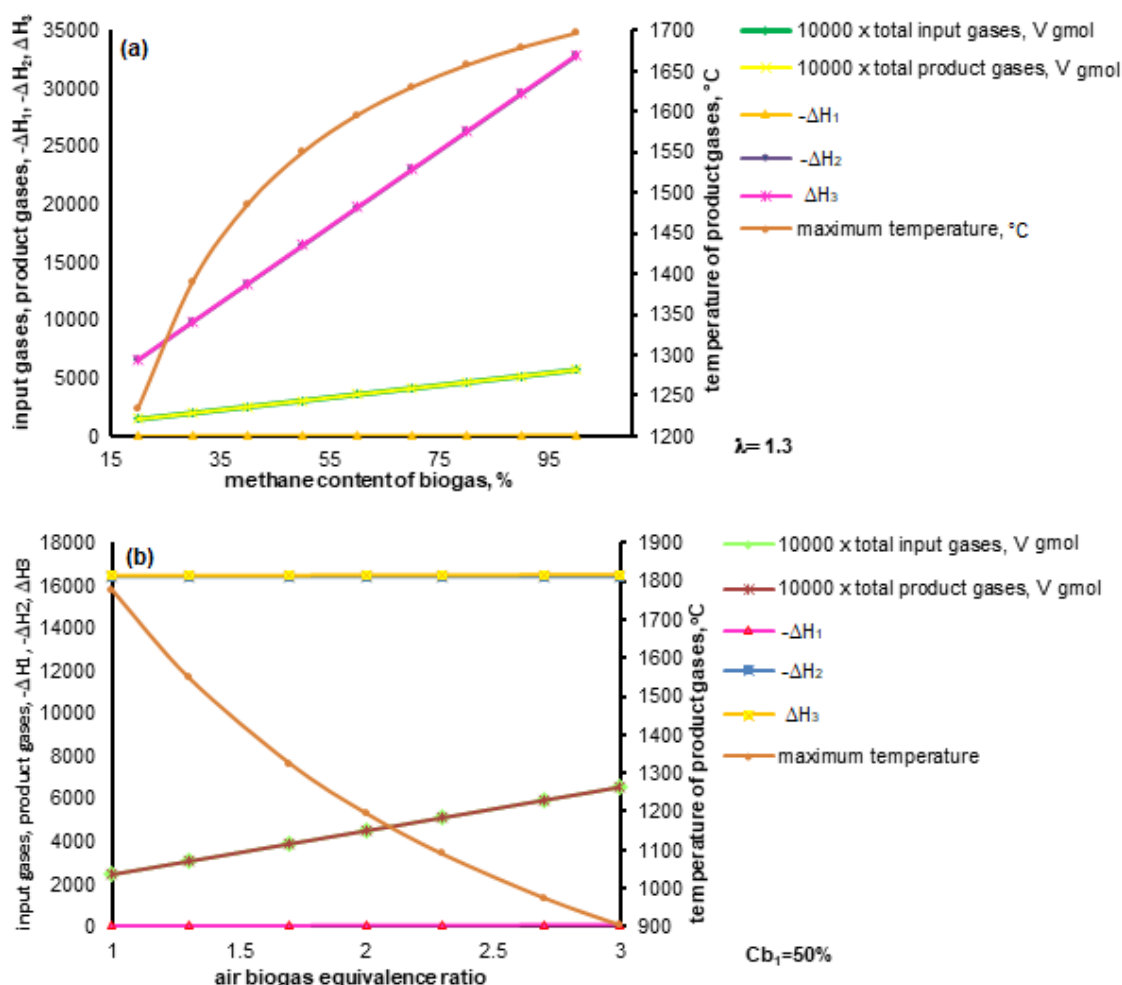


Fig 5. Total input gases, total product gases, $-\Delta H_1$, $-\Delta H_2$, ΔH_3 , and maximum temperature of combustion product (a) in various methane content of biogas, and (b) in various air biogas equivalence ratio

Based on the alternative process path in Fig. 3, the maximum temperature of product gases from biogas combustion is obtained from the sensible heat that was released from the input gases to reach the combustion reaction temperature and from the heat released from the combustion of methane in biogas (in actual process, the heat that was released from the combustion reaction directly increased the combustion gases temperature), however, because the differences between input gases temperature (30°C) and combustion reaction temperature (25°C) was not significant, the phenomena that can be seen in Fig. 5a and 5b show that almost all heat that be used to increase the temperature of combustion gases was derived from the heat of combustion of biogas, and very little heat derived from the sensible heat released from the reactant. This trend was showed by the position of line $-\Delta H_1$, $-\Delta H_2$, and ΔH_3 in Fig. 5a and 5b.

The position of line $-\Delta H_2$ and ΔH_3 were almost coincident, the value of ΔH_3 slightly higher than the value

of $-\Delta H_2$, in the other hand the position of line $-\Delta H_1$ was very low. The value of $-\Delta H_1$ as much as 22.3737V Joule in methane content 20% and air biogas equivalence ratio 1.3 and 94.0321V Joule in methane content 50% and air biogas equivalence ratio 3, were not significant compared with the value of $-\Delta H_2$ as much as 6565.8553V Joule in methane content 20% and air biogas equivalence ratio 1.3 and 16414.6382V Joule in methane content 50% and air biogas equivalence ratio 3. When the methane content was 100% and the air biogas equivalence ratio was 1.3 the value of $-\Delta H_2$ is approximately of 32829.2765V Joule. The value of $-\Delta H_2$ just slightly lower than the value of ΔH_3 as much as 6588.2290V Joule in methane content 20% and air biogas equivalence ratio 1.3 and 16508.6699V Joule in methane content 50% and air biogas equivalence ratio 3.

Fig. 5a show that the maximum temperature of combustion product gases tend to increase with the increasing of methane content, as the effect of the

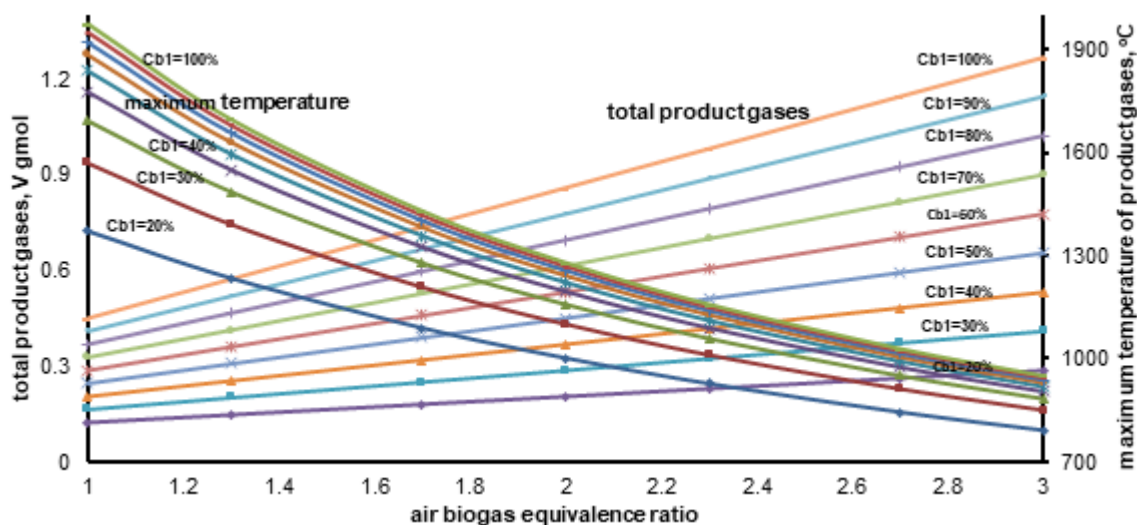


Fig 6. Total combustion gases and the maximum temperature

increasing of the heating value of biogas. In the other hand, although the value of the negative combustion enthalpy ($-\Delta H_2$) is linearly increase with methane content however the increasing of maximum temperature of combustion gases tend to decrease with the increasing of methane content (can be seen from the line of temperature that not linier but it is curved with slope to be smaller by the increasing of methane content). There are a significant increase of amount of combustion product gases from the combustion of biogas with high level methane due to the increasing of the amount of feed air into combustion chamber that further more imply in the increasing of excess O_2 and N_2 inert in the combustion product gases. Those gases need sensible heat to reach same temperature with others component in combustion product, that further more decrease the increasing of maximum temperature reached. This analysis in accordance with Colorado research [37], in which the increased amount of inert gases cool down the reactions lowering the temperature of the chamber.

The influence of inert component and excess O_2 from the combustion air on maximum temperature of product gases can be seen clearly in Fig. 5b. In the same methane content (same heating value of biogas), the increasing of air biogas equivalence ratio will effect in the significant increasing of the amount of combustion gases with excess O_2 and N_2 inert that furthermore decrease the maximum temperature. When the methane content is 50% and air biogas equivalence ratio is 1, the maximum temperature reached is up to 1700 °C, and significantly decrease to below 1195 °C when the air biogas equivalence ratio is 2. The overall result about the product gases and the maximum temperature reached is presented in Fig. 6.

In accordance with the trend in Fig. 5b, Fig. 6 show that the maximum temperature of product gases tend to

decrease with the increasing of air biogas equivalence ratio due to the present of a lot of inert component (excess O_2 and N_2 inert from combustion air) in the combustion product gases.

The trend in Fig. 5a also can be seen clearly in Fig. 6, the temperature of combustion gases was tend to increase with the increasing of methane content in biogas, showed by the position of temperature line in the chart that was higher in the higher methane content. The amount of combustion gases was from 0.12271V gmol in methane content 20% and air biogas equivalence ratio 1 to 1.26798V gmol when the methane content 100% and air biogas equivalence ratio 3. The maximum temperature of combustion gases was approximately between 791.75382 °C in methane content 20% and air biogas equivalence ratio 3 and 1974.95080 °C in methane content 100% and air biogas equivalence ratio 1.

In the application of biogas system, the methane content of biogas will depend on the type of organic material used as substrate and the purification process carried out, and, the amount of input air need to be designed according to the value of lower and upper flammability limit so that the combustion reaction can well occur. According to Matheson [38], the flammable range of methane was 5–15%. When the combustion air is limited or only in the amount of stoichiometric need, uncompleted combustion may occur and CO will present in the combustion gases, this CO still have calorific value that further more decrease the temperature reached. In the other hand the big amount of combustion air will also decrease the temperature of combustion gases, and too big amount of air will cause the concentration of methane in the input gases below the lower flammability limit so that the combustion reaction did not occur [39].

Table 1. Comparison with previous study

Methane content, %	Temperature from simulation, °C	Temperature from previous study, °C
40	883–1692	~1427–1479 [29]
51	906–1783	600–1200 [31]
60	919–1838	877–957 [28], ~1500 [28]~1427-1521 [29], 1587 [27], 907 [37]
61	920–1843	~1427–1566 [29]
65	924–1862	1852 [5]
100	950–1974	1952 [5], ~1427–1567 [29]
45–100	894–1974	1727–1952 [5]
20–100	7911974	895–2085 [26]

Comparison with Previous Researches

The result of the simulation in this research then compared with the result of previous researches, as can be seen in Table 1.

Information in Table 1 show that largely the value of combustion temperature from previous researches was in the range value of maximum temperature from the simulation. Slightly differences can be seen when the simulation results were compared with the numerical study done by Noor et al. [28], and experimental result done by Colorado et al. [37], in where the lowest temperature of the range of average temperature [28] and the average temperature [37] resulted from previous researches were slightly lower than the lowest temperature value obtained from the simulation. Since the temperatures from previous researches [28,37] were the average temperatures, those temperatures will always be lower than the maximum temperatures. The presence of little unburned methane [28], little incomplete combustion that produce CO [28,37], and little NO_x formation [37] will also decrease the temperature. Since this simulation was done in complete condition, the temperature obtained will be higher. The maximum temperature obtained by Noor et al. for air oxygen mole fraction 20% approximately of 1500 °C [28] was in the range of maximum temperature obtained in this simulation.

The values of temperature obtained by Dahiya et al. (for non-seeded combustion product) [5] also in the range of simulation result, however because the data of Dahiya et al. were obtained for stoichiometric condition, the value of the temperature were in the high value of the range of temperature from the simulation. Any lower temperatures from the simulation were obtained because the simulation was done in the excess of air and the higher temperature obtained because the simulation was done for complete combustion. Dahiya et al. research considered the dissociation reaction of the product and component gases in the combustion process that imply in the decreasing of temperature achieved.

The lowest temperature value obtained by Biogas Technology Limited [31] was lower approximately of 300 °C than the lowest temperature from the simulation. This

differences could be caused by unburned methane (when the temperature fall below 1000 °C, the lower temperature provides a documented destruction efficiency [31]), incomplete combustion, endothermic reaction in the formation of NO_x, and the effect of wind at the stack [31]. CO and NO_x were exist in the exhaust gases for all of the experiment conducted. When the temperature was 657 °C, CO in the exhaust gases amounted as 538.34 mg/m³ [31]. For temperature 875 °C, CO in the exhaust gases amounted as 182.87 mg/m³ [31].

The temperature resulted from the simulation were approximately 103–110 °C below the theoretical flame temperature presented by Caine [26]. The differences of the lowest temperature (the lowest value of the range of temperature) obtained could be caused by the higher air biogas equivalence ratio simulated in this research (up to 3, the Caine research only conducted up to air biogas equivalence ratio about 2) that caused the lower temperature obtained from simulation. In the other hand the differences of the highest temperature (the highest value of the range temperature obtained) could not clearly be analyzed due to the limited information from Caine [26]. Since the highest temperature was obtained when the air biogas equivalence ratio amounted as 1 and methane content as 100% that was simulated in this research and presented in the previous research [26], those highest temperatures should be not significant different. It was predicted that the differences could be caused by the differences of the assumption used in the calculation or could be caused by the differences of initial temperature of input air and biogas.

CONCLUSION

The product composition and the maximum temperature that can be achieved from biogas combustion varies depend on the methane content of biogas and the designed air biogas equivalence ratio. From complete combustion, the product gases will be CO₂, H₂O, excess O₂, and inert N₂. More than 50% component in the combustion gases was N₂, an inert material that was carried along with the combustion air. For the combustion of V m³ biogas, the total amount of

product gases can reach 0.12271V up to 1.26798V g/mol in the range methane content of 20-100% and air biogas equivalence ratio 1-3. The maximum temperature of product gases can reach more than 700 °C when the methane content is 20% and more than 1900 °C when the methane content can reach 100%.

ACKNOWLEDGEMENT

The authors gratefully thank to Ghalya Pikra, M.T., Nur Rohmah, M.T., Arifin Santosa, S.T., and all researchers in Research Centre for Electrical Power and Mechatronics, Indonesian Institute of Sciences. The author would also thank to Ministry of Research, Technology, and Higher Education for funding support through "Program Pendukung Beasiswa SAINTEK Kementerian Riset, Teknologi, dan Pendidikan Tinggi 2018".

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