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The Effect of Air Flow Rate and Ratio Between Coal and Coconut Shell on Heat Energy Produced in an Updraft Gasifier

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Abstract. At present, energy needs are increasing almost in all sectors of human life, especially in developing countries. The world's petroleum reserves are depleting, while the need for fuel continues to increase. The use of alternative fuels can be a solution to overcome the problem of energy needs. Biomass is one of several alternative energy sources and has considerable potential to be processed into fuel and easy to obtain. Biomass raw materials can come from plantation or agricultural waste. One of the solid biomass fuels is coconut shell. Coconut shells are biomass derived from coconut plants. The use of coal as fossil fuel is also expected to replace the role of fuel oil. South Sumatra is one of the regions that have a large enough coal reserve potential in Indonesia. Co-gasification is the development of a gasification process that converts two mixtures of solid fuels such as biomass and coal by using air supply from the blower and producing a combustible gas. Therefore, this study aims to determine the effect of air mass flow rates and the fuel mixture ratios of coal and coconut shell on heat energy produced in an updraft gasifier. The research method used was experimented using an updraft type gasifier. This type is the simplest type by producing the output gas from the top. The results show that the fuel mixture ratio of coal and coconut shell as much as 20% : 80% with the air mass flow rate of 4.33 kg/h has the lowest fuel consumption rate of 2.60 kg/h. Furthermore, the fuel mixture ratio of 20% : 80% with air mass flow rate of 12.99 (kg/h) produces the biggest total heat of 1381.46 (kJ). Otherwise, the fuel mixture ratio of 10% : 90% with air mass flow rate of 4.33 (kg/h) produces the smallest total heat of 654.42 (kJ). The results also show that the fuel mixture ratio of 20%: 80% with air mass flow rate of 12.99 (kg/h) yields the highest temperatures in drying, pyrolysis, reduction and oxidation or combustion zones of 125.4 C, 156.2 C, 329.2 C and 589.0 C, respectively.

1. Introduction

The development of human civilization accompanied by the development of science and technology as well as an increase in the current population greatly influence the ever-increasing energy needs. The provision of energy to be able to meet rising energy needs in all sectors of life such as the industrial, transportation and household sectors is a serious problem in an area such as South Sumatra. One of the energy sources that can still be relied on and developed into renewable energy is coal gasification and biomass [1].

Biomass can also be an alternative energy source and can be very useful if it can be processed into renewable energy and can be used for the smallest things such as cooking or large-scale needs for electricity generation. One of the useful biomass at this time can come from coconut shell which is waste from coconut fruit which can also be converted into renewable energy along with coal into gas capable of burning through a gasification process. By knowing the composition and chemical content contained in coconut shells and coal, the material can be used as an alternative energy source.

Gasification is one example of a thermochemical conversion process in which solid fuels will be converted to a gas capable of combustion due to a partial oxidation reaction or the amount of oxidant that is less than the requirement [2]. The gasification process takes place at temperatures between 800°C to 1800°C, the right temperature depends on the characteristics of the fuel used. Another development of the gasification process is co-gasification technology that can be used to convert two solid fuel mixtures such as biomass and coal to produce gas capable of combustion. The type of gasification based on fluidisation is divided into moving or fixed bed gasification, fluidized bed gasification, and entrained flow. Furthermore, from the type of fixed bed gasification based on the direction of gas flow, it is divided into updraft gasifier, downdraft gasifier and crossdraft gasifier [2].

This research was conducted using updraft type gasification to study the effect of air mass flow rate and the fuel mixture ratio of coal and coconut shell to the total thermal energy produced. Therefore, this study aims to: (1) Analyze the fuel consumption rate (FCR) generated from an updraft gasifier by varying the air mass flow rate and the fuel mixture ratio of coal fuel and coconut shell. (2) Analyzing the temperatures of zones of the gasification process (3) Analyzing the total heat that can be utilized from the useful gas.

2 Literature Review

2.1 Biomass

Biomass is an alternative energy source that can be developed in Indonesia. The potential for biomass energy that can be used is very large, this is evident from the abundant source of biomass. Some examples of biomass are all organic things such as wood, food crops, waste and animal waste as well as agricultural waste where biomass resources derived from agricultural crops and plantations can be empty oil palm bunches, coffee husks, rice husks, bagasse, straw, coconut shell, palm shell, leaves and others [3].

2.1.1 Biomass of Coconut Shell. Biomass is an organic material produced through photosynthetic processes in the form of products or waste. One type of biomass that can be used as renewable energy is coconut shell from coconut tree plantation waste that has not been used optimally. Biomass energy needs to be developed by using one method to produce alternative energy in the form of gas through a gasification process.

2.2 Coal

According to the 2015 Ministry of Energy and Mineral Resources data, South Sumatra's coal resource potential in 2015 is quite large where there are 51901.93 million tons or around 40.9% of the national coal resource potential, which is 126609.34 million tons while the potential of coal reserves in South Sumatra around 12274.72 million tons or around 38.0% of the potential of national coal reserves, namely 32263.68 million tons. Most of the coal resources are classified as low rank coal where the coal in South Sumatra has a range of heat values from 4200-7785 kcal/kg with a humidity of 4.40% - 41.00% , the flying substance content was 32.40% - 43.50% and the ash and sulphur content, in general, was quite low, i.e less than 10% and less than 1% respectively. Low rank coal properties can be upgraded for improving fuel quality capable of using in advanced power plants [4]

2.3 Gasification

Gasification is a process whereby carbonated fuels such as coal or solid biomass are broken down into carbon monoxide, hydrogen, carbon dioxide, and hydrocarbon molecules in chemical reactors using oxygen or steam as a gasification agent to produce combustible gases. Gas capable of combustion produced by the gasification process is called a producer gas which is a mixture of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), and carbon dioxide (CO_2) with a limited air supply between 20% to 40% stoichiometric air. Gasification can not only be used for coal gasification but can also be applied to gasification processes that use a fuel mixture in the form of a mixture of coal and biomass that can be developed into more efficient gasification technology [5]

2.4 Types of Gasification Reactors
Based on the fluidization type, this type of gasifier can be divided into fixed bed gasification, moving bed gasification, fluidized bed gasification, and entrained bed gasification [2].

2.4.1 Fixed Bed Gasifier. Fixed bed gasifier or moving bed gasifier is the oldest coal gasification technology. The type of fixed bed gasifier or moving bed gasifier is divided into three types based on gasification flow including an updraft gasifier, a downdraft gasifier, and a crossdraft gasifier. Updraft gasifier (Fig. 1) is a widely used gasification reactor where the combustion process takes place in a grate area. The resulting gas producer comes out through the top of the gasifier while the ash is taken from the bottom of the gasifier [6]

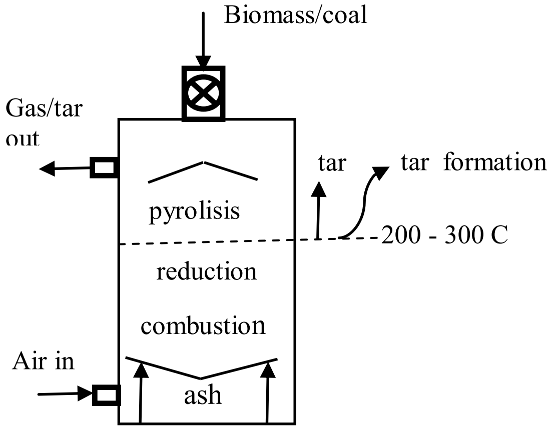

Figure 1. Updraft Gasifier

2.5 Stages of the Gasification Process
Figure 2 shows the stages of the gasification process through chemical reactions at high temperatures between fuels with gasification agents such as air

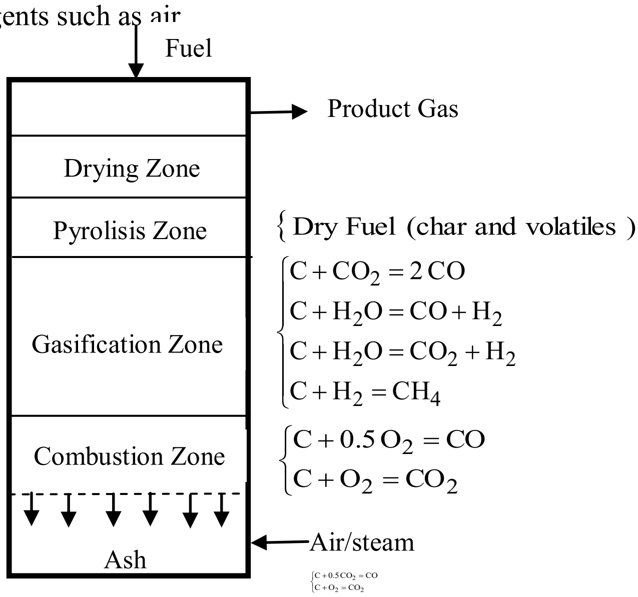

Figure 2. Updraft Gasifier Gasification Stages [2]

The gasification process consists of four stages of the process with various temperature conditions that are appropriate at each stage including drying, pyrolysis or thermal decomposition, oxidation or

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combustion, and reduction. Drying, pyrolysis and reduction processes are heat absorbing (endothermic) where the heat generated from the oxidation process is used again in the process of drying, pyrolysis, and reduction [7].

2.6 Calculation in the Gasification Process
According to [2], the parameters that need to be considered in the gasification process are as follows.

2.6.1. Gasification Temperature. Gasification temperature must be high because in the first stage gasification is drying because high temperatures can also affect producing flammable gases.

2.6.2. Air Mass Flow Rate. Air mass flow rate calculation can be formulated as follows.

$$\dot{m}_{air} = \rho_{air} \text{ x } A \text{ x } V \quad (1)$$

where:

$\dot{m}_{air}$ = air mass flow rate (kg/s) ; ρ_{air} = air density (kg/m^3)
A = channel cross-sectional area (m^2) ; V = air flow velocity (m/s)

2.6.3. Fuel Consumption Rate (FCR). Biomass needed in the gasification process can be calculated using the following formula.

$$FCR = \frac{W_{gf}}{O_t} \text{ (kg/h)} \quad (2)$$

where:
W_{gf} = weight of gasified fuel (kg) ; O_t = operating time (h)

2.6.4. Air Fuel Ratio (AFR). AFR is the ratio of the air mass flow rate and the mass flow rate of the fuel used. AFR can be calculated by using the following equation.

$$AFR = \frac{\dot{m}_{air}}{\dot{m}_{fuel}} \quad (3)$$

where:
$\dot{m}_{air}$ = air mass flow rate (kg/s) ; $\dot{m}_{fuel}$ = fuel mass flow rate (kg/s)

2.6.5. Percentage of Char. The percentage of Char is the ratio of the amount of charcoal produced with the amount of biomass needed. The percentage of char that can be calculated using the formula:

$$\%char = \frac{\text{weight of char (kg)}}{\text{weight of fuel (kg)}} \text{ x } 100\% \quad (4)$$

2.6.6. Heat Energy. The heat that will be generated by the gas capable of burning for boiling and evaporation of water can be calculated in terms of energy units.

2.6.6.1. Sensible heat. Sensible heat (Q_s) can be calculated using the following formula.

$$Q_s = m_w \text{ x } c_p \text{ x } (T_2 - T_1) \quad (5)$$

where:
m_w = mass of water (kg) ; c_p = average specific heat of water (kJ/kg.C)
T_1 = initial water temperature (C) ; T_2 = final water temperature (C)

The sensible heat rate, $\dot{Q}_s$ (W) can be calculated as the sensible heat, Qs (kJ) divided by the water boiling time (s) as follows.

$$\dot{Q}_s = \frac{Q_s}{t_s} \text{ (W)} \quad (6)$$

where:

t_s = water heating time (s)

2.6.6.2. Latent Heat. The latent heat (Q_L) can be calculated by using the following formula.

$$Q_L = m_s \text{ x } h_{fg} \quad (7)$$

where:
Q_L = latent heat (kJ) ; m_s = mass of formed steam (kg)
h_{fg} = evaporation heat (kJ/kg)

The latent heat rate, $\dot{Q}_L$ (W) can be calculated as the latent heat, Q_L (kJ) divided by the evaporation time of water, t_s (s) as follows.

$$\dot{Q}_L = \frac{Q_L}{t_s} \text{ (W)} \quad (8)$$

The mass of steam produced (m_s)can be calculated by using equation (9) as follows.

$$m_s = m_{a2} - m_{a1} \quad (9)$$

where:
m_{a1} = initial water mass (kg) ; m_{a2} = final water mass (kg)

2.6.7. Thermal Efficiency of Furnace. The thermal efficiency of the furnace (η_{th}) can be calculated as the ratio of the total rate of heat energy used for boiling and evaporation to the rate of heat energy produced by the fuel formulated as follows [8].

$$\eta_{th} = \frac{\dot{Q}_L + \dot{Q}_s}{Q_f \text{ x } \dot{m}_f} \quad (10)$$

where:
Q_f = fuel calorific value (kJ/kg) ; $\dot{m}_f$ = fuel mass flow rate (kg/s)

3. Research Methodology

3.1 Research Flow Chart

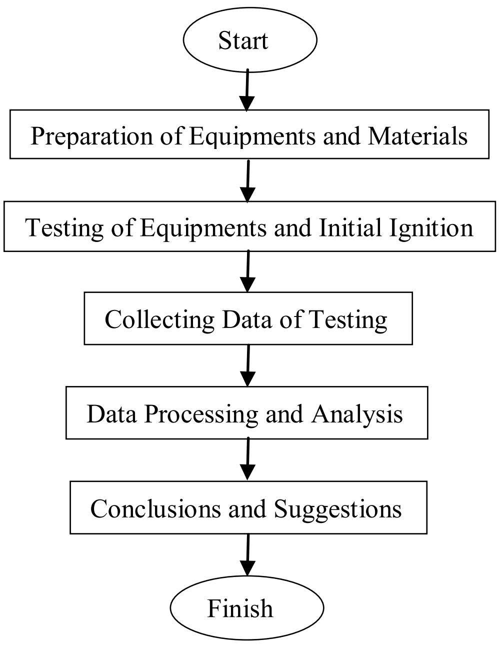

Figure 3. Research Flow Chart

3.2. Research Methods

This study applies an experimental method using an updraft type gasification reactor with a fuel mixture of coal and coconut shell and with a mass capacity of 5 kg, that can be seen in Figure 4.

3.3. Experimental equipment layout

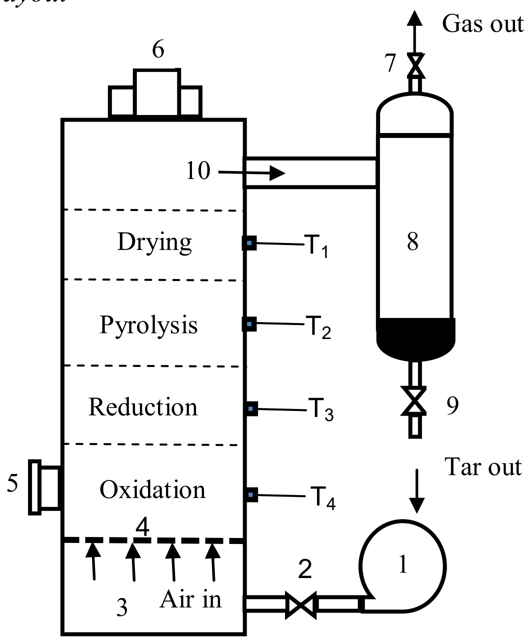

Figure 4. Experimental Equipment Schematic

Description of Figure 4:

1 = Blower	; 8 = Cyclone
2 = Air regulating valve	; 9 = Tar drain valve
3 = Ash collection case	; 10 = Flammable gas flow
4 = Grate	; T_1 = Drying temperature
5 = Fuel ignition port	; T_2 = Pyrolisis temperature
6 = Fuel inlet port	; T_3 = Reduction temperature
7 = Flammable gas regulating valve	; T_4 = Oxidation temperature

3.4. Materials

The fuel used in this experiment is a mixture of coconut shell and coal which has been determined its composition.

3.5. Experimental Procedure

The updraft type gasification equipment used in this study is made of steel with a thickness of about 5 mm. The procedure for operating it is as follows.

- First, make sure that the blower condition can operate at a constant speed and carry out the first ignition using kerosene or coconut shell charcoal and wait until a steady flame is obtained.
- Then, the initial fuel can be fed into the reactor for initial combustion of 0.5 kg of coal and coconut shell mixture with a certain ratio.
- Furthermore, the remaining fuel mixture is put into the reactor for complete combustion of one cycle. This gasification process is carried out for several cycles with variations in the ratio of fuel mixture between coal and coconut shell and variations in air flow rates.

- Data collection in this gasification process was carried out by variations in air mass flow rates of 4.33 kg/h, 8.66 kg/h and 12.99 kg/h. Measurement of the duration of operation and the flame on is done using a stopwatch.
- After the testing procedure is completed, it should be noted again to turn off the timer which indicates that the operating time has been completed.
- The gasifier cover is opened first so that no air is trapped in the reactor then the remaining fuel can be removed after the gasifier is cool enough and the remaining mass of fuel can be weighed to get the total mass of residual fuel.

4. Results and Discussion

4.1. Fuel Testing Results

In this study, the proximate analysis was carried out at the Laboratory of the Department of Energy and Mineral Resources of South Sumatra Province, and the results of the tests are shown in Table 1.

Table 1. Proximate analysis of a fuel mixture of coal and coconut shell

Ratio of coal and Coconut shell	Heating value (cal/g)	Moisture content (%adb)	Ash content (%adb)	Volatile matter (%adb)	Fixed carbon (%adb)
20% : 80%	4480	13.94	1.44	63.50	21.12
15% : 85%	4402	13.44	1.25	65.03	20.28
10% : 90%	4383	12.47	0.95	67.18	19.40

4.2. Test Result Data

Testing using this updraft type gasification reactor will be conducted with variations in air mass flow rates and fuel mixture ratios of coal and coconut shell that can be seen in Table 2, Table 3 and Table 4.

Table 2. Temperature measurement results for each zone in the reactor

Air mass flow rate (kg/h)	Ratio of coal and Coconut shell	T_1 (°C)	T_2 (°C)	T_3 (°C)	T_4 (°C)	T_{flame} (°C)
	20% : 80%	110.2	128.8	267.2	505.6	522.2
4.33	15% : 85%	105.6	124.6	249.4	500.6	515.2
	10% : 90%	99.8	121.2	238.6	489.0	501.4
	20% : 80%	116.8	140.8	317.2	542.4	563.5
8.66	15% : 85%	112.8	133.8	305.8	524.6	542.3
	10% : 90%	110.0	131.2	302.8	513.4	513.4
	20% : 80%	125.4	156.2	329.2	589.0	603.7
12.99	15% : 85%	124.2	151.8	321.2	566.6	581.3
	10% : 90%	119.4	145.4	318.4	544.6	565.7

Table 3. Fuel consumption rate (kg/h) at various air mass flow rates (kg/h) and fuel mixture ratios of coal and coconut shell

Air mass flow rate (kg/h)	Ratio of coal and Coconut shell	Operating time (min)	Initial fuel mass (kg)	mass of residual fuel (kg)	mass of gasified fuel (kg)
	20% : 80%	67.0	5	2.10	2.90
4.33	15% : 85%	64.0	5	1.92	3.08
	10% : 90%	60.0	5	1.85	3.15
	20% : 80%	59.5	5	1.90	3.10
8.66	15% : 85%	55.0	5	1.72	3.28
	10% : 90%	53.0	5	1.50	3.50

	20% : 80%	49.0	5	1.72	3.28
12.99	15% : 85%	39.0	5	1.66	3.34
	10% : 90%	37.0	5	1.40	3.60

Table 4. The mass of formed steam (kg) and duration for heating and evaporation processes (min)

Air mass flow rate (kg/h)	Ratio of coal and Coconut shell	Initial water mass (kg)	mass of residual water (kg)	mass of formed steam (kg)	Duration for heating (min)	Duration for evaporation (min)
	20% : 80%	1.0	0.72	0.28	16.6	8.6
4.33	15% : 85%	1.0	0.79	0.21	17.3	5.7
	10% : 90%	1.0	0.84	0.16	18.6	4.2
	20% : 80%	1.0	0.64	0.36	12.2	8.7
8.66	15% : 85%	1.0	0.73	0.27	13.6	5.7
	10% : 90%	1.0	0.82	0.18	14.8	3.3
	20% : 80%	1.0	0.52	0.48	8.7	7.8
12.99	15% : 85%	1.0	0.66	0.34	10.8	4.3
	10% : 90%	1.0	0.80	0.20	11.3	2.1

4.3. Processing of test results

From the test results, data obtained then an analysis is performed on the thermal efficiency of the gasification equipment used in this experiment. Calculation of furnace efficiencies is carried out at various air mass flow rates and mixture ratios of coal and coconut shell. The calculation is done for the air mass flow rate of 4.33 kg/h and the mixture ratio between coal and coconut shell at 20% : 80%. The calculation is done for the air mass flow rate of 4.33 kg/h and the mixture ratio between coal and coconut shell at 20%: 80%. Gasification process on a fuel mixture of coal and coconut shell can be evaluated using the following formula.

- Fuel consumption rate, $FCR = \frac{W_{gf}}{O_t} \text{(kg/h)} = \frac{2.9\ \text{kg}}{1.12\ \text{h}} = 2.60\ \text{(kg/h)}$

  where:
  W_{gf} = weight of gasified fuel (kg) = 2.9 (kg) ; O_t = operating time (h) = 1.12 (h)

- Air fuel ratio, $AFR = \frac{\dot{m}_{air}}{\dot{m}_{fuel}} = \frac{4.33\ \text{kg/h}}{2.60\ \text{kg/h}} = 1.67$

  where:
  $\dot{m}_{air}$ = air mass flow rate (kg/h) = 4.33 (kg/h) ; $\dot{m}_{fuel}$ = fuel mass flow rate (kg/h) = 2.60 (kg/h)

- Air mass flow rate, $\dot{m}_{air} = \rho_{air}\ \text{x}\ A\ \text{x}\ V = 1.16\ \text{x}\ 0{,}000346\ \text{x}\ 10800 = 4.33\ \text{(kg/h)}$

  where:

  ρ_{air} = air density (kg/m^3) = 1.16 (kg/m^3) ; V = air flow velocity (m/h) = 10800 (m/h)
  A = channel cross-sectional area (m^2) = 0.000346 (m^2)

- Sensible heat for heating water, Q_s = m x c_p x ($T_2 - T_1$) (kJ) = 1 x 4.190 x (100-30) = 293.30 (kJ)

  where:
  m = initial mass of water (kg) = 1.0 (kg) ; c_p = specific heat of water (kJ/kg.C) = 4.190 (kJ/kg.C)
  T_1 = initial water temperature (C) = 30 (C) ; T_2 = evaporation temperature of water (C) = 100 (C)

- The sensible heat rate, $\dot{Q}_s = \frac{Q_s}{t_s} = \frac{293.30\,(kJ)}{994\,(s)} = 0.30\,(kW)$

  where: Q_s = sensible heat (kJ) = 293.30 (kJ) ; t_s = water boiling time (s) = 994 (s)

- The latent heat, $Q_L = m_s \times h_{fg}$ = 0.28 (kg) x 2257 (kJ/kg) = 631.96 (kJ)

  where: m_s = mass of steam (kg) = 0.28 (kg) ; h_{fg} = evaporation heat (kJ/kg) = 2257 (kJ/kg)

- The latent heat rate, $\dot{Q}_L = \frac{Q_L}{t_s} = \frac{631.96\,(kJ)}{514\,(s)} = 1.23\,(kW)$

  where:

  Q_L = latent heat (kJ) = 631.96 (kJ) ; t_s = the evaporation time of water (s)= 514 (s)

- Thermal efficiency of furnace, $\eta_{th} = \frac{\dot{Q}_L + \dot{Q}_s}{Q_f \text{ x } \dot{m}_f} = \frac{(0.30 + 1.23)\,kW}{18757.33 (kJ/kg) \text{ x } 0.0007\,(kg/s)} = 0.1127$

  where:

  Q_f = fuel calorific value (kJ/kg) = 188757.33 (kJ/kg) ; $\dot{Q}_s$ = sensible heat rate (kW) = 1.23 (kW)

  $\dot{m}_f$ = fuel mass flow rate (kg/s) = 0.0007 (kg/s) ; $\dot{Q}_L$ = latent heat rate (kW) = 0.30 (kW)

4.4. Effects of air mass flow rate and fuel mixture ratio on fuel consumption rate (FCR)

Figure 5 shows that the fuel mixture ratio of coal and coconut shell as much as 20%:80% with the air mass flow rate of 4.33 kg/h has the lowest FCR value of 2.60 kg/h. Furthermore, in the fuel mixture ratios of 15%:85% and 10%:90% at the same air mass flow rate of 4.33 kg/h, it can be seen that the FCR increases to 2.89 kg/h and 3.15 kg/h, respectively. The highest FCR value of 5.84 kg/h was obtained at the fuel mixture ratio of 10%:90% and air mass flow rate of 12.99 (kg/h). This is caused by the more the amount of coconut shell in the fuel mixture will decrease the calorific value of the fuel mixture.

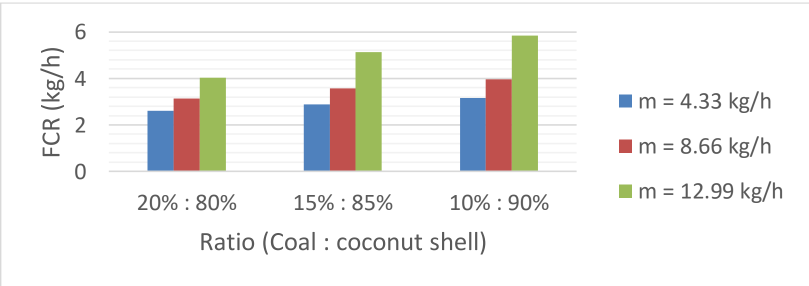

Figure 5. Effect of air mass flow rate (kg/h) on FCR (kg/h) at various fuel mixture ratios of coal and coconut shell

Figure 5 also shows that increase the air mass flow rate will increase fuel consumption rate (FCR) at all fuel mixture ratios of coal and coconut shell.

4.5. Effects of air mass flow rate and fuel mixture ratio on zones temperature in the reactor (FCR)

Figure 6, Figure 7 and Figure 8 show that an increase in the air mass flow rate results in an increase in the temperatures of the gasification zones in the reactor at each ratio of the applied fuel mixture.

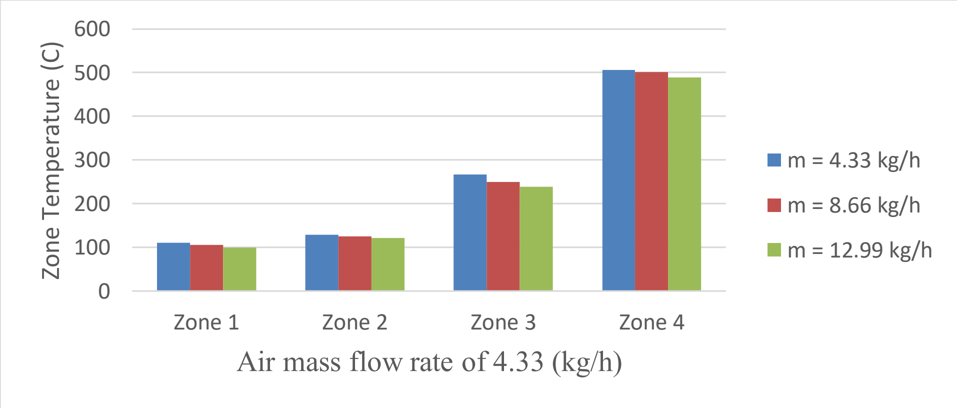

Figure 6. Effect of the fuel mixture ratio of coal and coconut shell on zone temperature (C) at air mass flow rate of 4.33 (kg/h)

Figure 6 also shows that the highest temperature of each zone in the gasifier is obtained at the fuel mixture ratio of 20% : 80%, otherwise, the lowest temperature of each zone is found at the fuel mixture ratio of 10% : 80%.

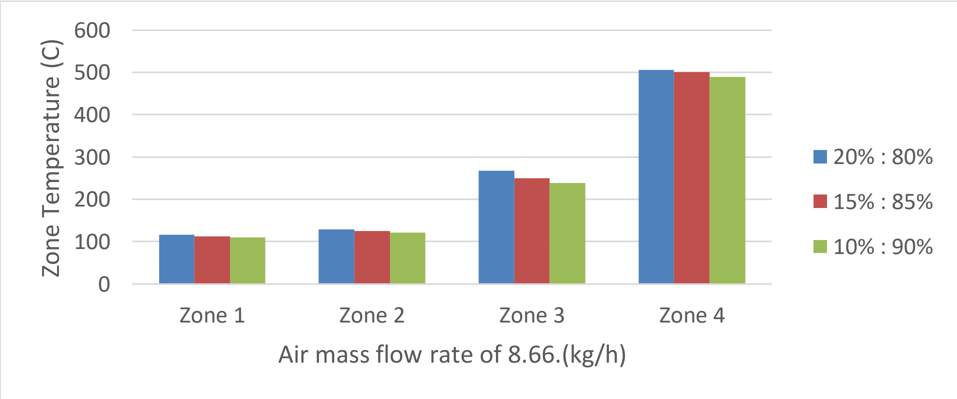

Figure 7. Effect of the fuel mixture ratio of coal and coconut shell on zone temperature (C) at air mass flow rate of 8.66 (kg/h)

Figure 7 also shows that the highest temperature of each zone in the gasifier is obtained at the fuel mixture ratio of 20% : 80%, otherwise the lowest temperature of each zone is found at the fuel mixture ratio of 10% : 80%. Zone 1 is the drying zone having the lowest temperature for each fuel mixture ratio of coal and coconut shell while zone 4 is the combustion zone having the highest temperature for each fuel mixture ratio. Zone 2 and zone 3 are the pyrolisis and the reduction zones.
Figure 8 shows that the highest temperature of each zone in the gasifier is obtained at the fuel mixture ratio of 20%:80%, otherwise, the lowest temperature of each zone is found at the fuel mixture ratio of 10%:80%. At air mass flow rate of 12.99 (kg/h), the lowest temperature of 119.4 (C) happens at the fuel mixture ratio of 10%:90% while the highest temperature of 603.7 (C) at a fuel mixture ratio of 20%:80%.

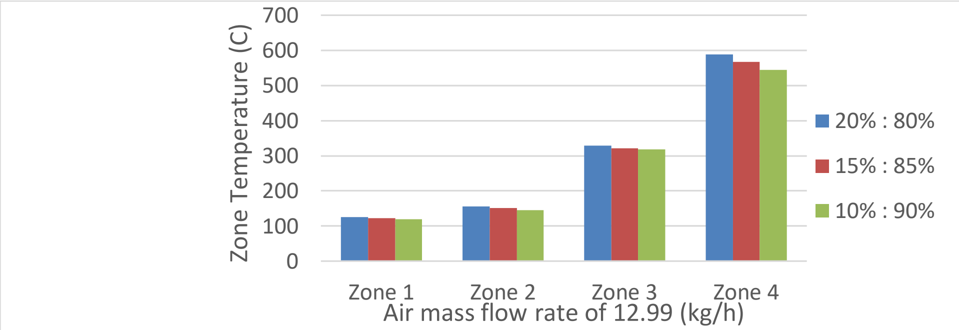

Figure 8. Effect of the fuel mixture ratio of coal and coconut shell on zone temperature (C) at air mass flow rate of 12.99 (kg/h)

4.6. Effects of air mass flow rate and fuel mixture ratio on total heat produced (Q_{tot})
Based on Figure 9 below, it can be seen that the fuel mixture ratio of 20%:80% with air mass flow rate of 12.99 (kg/h) produces the biggest total heat of 1381.46 (kJ). In addition, the fuel mixture ratio of 10%:90% with air mass flow rate of 4.33 (kg/h) produces the smallest total heat of 654.42 (kJ). Figure 9 also that an increase in the air mass flow rate results in an increase in the total heat produced in the gasification reactor at each ratio of the applied fuel mixture.

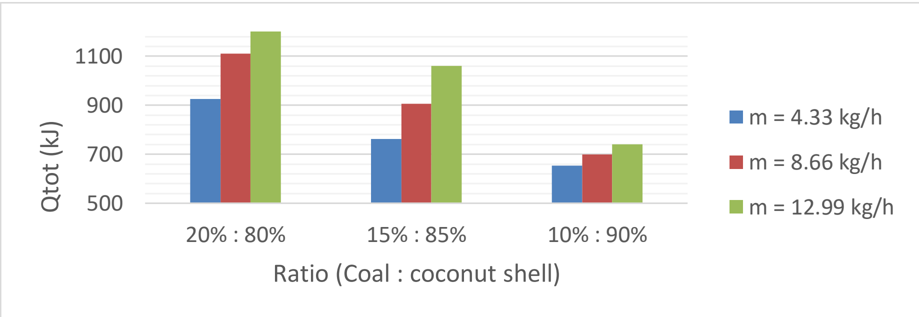

Figure 9. Effect of air mass flow rate and the fuel mixture ratio of coal and coconut shell on total heat produced (kJ)

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