



Effects of Fluidization Velocity and Equivalence Ratio on the Energy and Exergy of the Syngas Produced from Wheat Straw in A Dual-distributor Type Fluidized Bed Gasifier

Yaning Zhang^{1,2}, Abdel Ghaly^{2*}, Ali Ergudenler³ and Bingxi Li¹

¹School of Energy Science and Engineering, Harbin Institute of Technology, Harbin, China.

²Department of Process Engineering and Applied Science, Faculty of Engineering, Dalhousie University, Halifax, Canada.

³Air Quality Division, Policy and Planning Department, Greater Vancouver Regional District, Burnaby, British Columbia, Canada.

Authors' contributions

This work was carried out in collaboration between all authors. Author AE designed and performed the experimental study. Author YZ performed the theoretical analysis and wrote the first draft of the manuscript. Authors AG and BL managed experimental work, the analyses of the study, literature searches and the various drafts of the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Aim: Exergy is a measurement of how far a certain material deviates from a state of equilibrium with the environment. The aim of the study was to evaluate the energy and exergy of a syngas obtained from the gasification of wheat straw.

Methodology: A pilot scale dual distributor fluidized bed gasifier was used to gasify wheat straw at various fluidization velocities (0.28, 0.33 and 0.37m/s) and equivalence velocities (0.17, 0.20, 0.25

*Corresponding author: E-mail: abdel.ghaly@dal.ca;

and 0.35).

Results: The energy values of CO, H₂, N₂, CO₂, CH₄, C₂H₄ and C₂H₆ varied within the ranges of 3466.27-5790.62, 570.34-2025.86, 774.42-1973.99, 343.22-726.34, 1970.30-3694.93, 1225.03-3453.06 and 0.00-456.65 kJ/kg fuel, respectively. The overall energy distribution was CO>CH₄>C₂H₄>(H₂& N₂)>(CO₂ & C₂H₆). The results showed that increasing the FV from 0.28 to 0.37 (32.14%), initially decreased the total energy of syngas and then increased it, resulting in a net increase of 7.90-19.80% depending on the ER used. However, when the ER was increased from 0.17 to 0.35 (105.88%), the total energy of syngas increased by 61.82-77.70% depending on the FV used. The effect of the ER on the total energy of syngas was much greater than that of the FV. The exergy values of CO, H₂, N₂, CO₂, CH₄, C₂H₄ and C₂H₆ varied within the ranges of 3123.99-5200.75, 433.63-1548.33, 224.62-751.35, 262.97-751.35, 1780.38-3327.70, 1151.65-3237.09 and 0.00-425.11 kJ/kg fuel, respectively. The overall exergy distribution was CO>CH₄>C₂H₄>H₂>(C₂H₆& CO₂ & N₂). Increasing the FV from 0.28 to 0.37 (32.14%) increased the total exergy of the syngas by 8.62-21.35% depending on the ER used. On the other hand, increasing the ER 0.17 to 0.35 (105.88%) increased the total exergy of the syngas by 63.86-79.83% depending on the FV used. The effect of the ER on the total exergy of syngas was also much greater than that of the FV.

Conclusions: The exergy values of the syngas were lower than their energy values because the gas components contributed differently to the energy and exergy (the physical exergy of gas components are lower than the corresponding physical energy and the chemical exergy of combustible gases are lower than the corresponding chemical energy). The highest energy (16861.89kJ/kg fuel) and exergy (14532.49kJ/kg fuel) of syngas were obtained at the FV of 0.28 m/s and the ER of 0.35.

Keywords: Energy; exergy; syngas; gasification; wheat straw; fluidized bed gasifier; FV; ER.

1. INTRODUCTION

Burning of fossil fuels is a major source of greenhouse gas (GHG) emission that contributes to global climate change and current environmental and health problems. An agreement among the industrialized countries was signed in Kyoto in December 1997 to limit the utilization of fossil fuels and seek alternative energy sources [1]. Renewable energy, particularly agricultural and forestry biomass, is becoming more environmentally and economically attractive. Biomass can fix and store about 3.1×10^{21} J annually through photosynthesis [2,3]. Biomass is also CO₂-neutral and produces low emissions of SO_x and NO_x [4-6]. It is estimated that biomass can supply 25.8-31.7% of the world energy need [7].

Energy from biomass can be obtained through thermochemical conversions (gasification, combustion and pyrolysis) or biochemical conversions (biogas, bioethanol, biodiesel and biohydrogen). Gasification of biomass results in a gas mixture containing CO, CH₄, H₂, N₂, CO₂, H₂O and some hydrocarbons (C₂H₄ and C₂H₆). Very small quantities of NH₃, H₂S and tars are also produced [8]. The generated gas, commonly referred to as syngas can be combusted in burners, boilers and internal combustion engines

to produce heat, mechanical power or electricity. It can also be used to produce synthetic liquid fuels and lubricants as well as chemical commodities (methanol and ammonia) [9,10]. The advantages of biomass gasification are: (a) Minimum waste products, (b) lower gas emissions, (c) Higher recycling rates and (d) Higher energy efficiencies [8,9,11,12].

Energy and exergy can be used to evaluate energy sources. Energy is based on the first law of thermodynamics whereas exergy is based on both the first and second laws of thermodynamics together [13]. The energy of a gas mainly relates to its enthalpy and heating values whereas an extra state parameter (entropy) is included in the exergy analysis of the gas. More meaningful evaluations can be obtained with exergy analysis rather than energy analysis, since exergy is always a measure of the approach to the ideal condition [13].

The main objectives of this study were: (a) To determine the energy and exergy of a syngas produced from the gasification of wheat straw in a dual-distributor type fluidized bed gasifier and (b) To detail the distributions of energy and exergy values of syngas at various fluidization velocities and equivalence ratios.

2. ENERGY AND EXERGY OF SYNGAS

2.1 Energy of Syngas

The total energy of a flow gas can be written as the sum of various energy of the flow gas as follows [14]:

$$En = En^{ki} + En^{po} + En^{ph} + En^{ch} \quad (1)$$

Where:

- En : is the total energy of the gas stream (kJ/kg)
- En^{ki} : is the kinetic energy of the gas stream (kJ/kg)
- En^{po} : is the potential energy of the gas stream (kJ/kg)
- En^{ph} : is the physical (or sensible) energy of the gas stream (kJ/kg)
- En^{ch} : is the chemical energy of the gas stream (kJ/kg)

Zhang [15] reported that the kinetic energy and potential energy represent very small portions (0.000001-0.0003% and 0.00002-0.003%, respectively) of the total energy and can be neglected. Equation (1) can then be simplified to:

$$En = En^{ph} + En^{ch} \quad (2)$$

The syngas generated from biomass gasification is a mixture of $H_2, CO, CO_2, CH_4, C_2H_4, C_2H_6, N_2, O_2$, etc. The physical energy of syngas can be calculated from the following linear mixing equation [16]:

$$En^{ph} = \sum_i n_i h_i \quad (3)$$

Where:

- n_i : is the molar yield of gas component i (mol/kg)
- h_i : is the specific enthalpy of gas component i (kJ/kmol)

Based on the specific enthalpy of gases at the environmental state specified in Table 1 (temperature $T_0 = 25^\circ C$ and pressure $P_0 = 1$ atm), the specific enthalpy of gases at arbitrary temperatures can be obtained from the following equation [17]:

$$h = h_0 + \int_{T_0}^T c_p dT \quad (4)$$

Where:

- h : is the specific enthalpy of gas component at the arbitrary temperature (kJ/kmol)
- h_0 : is the specific enthalpy of gas at the environmental state (kJ/kmol)
- T_0 : is the environmental temperature (298.15K)
- T : is the temperature of the gas under an arbitrary condition (K)
- c_p : is the constant pressure specific heat capacity (kJ/kmolK)

The empirical equation of the constant pressure specific heat capacity is written as follows [17]:

$$\overline{c_p} = a + bT + cT^2 + dT^3 \quad (5)$$

Where:

a, b, c, d are the coefficients of constant pressure specific heat capacity (Table 2). The chemical energy of syngas is expressed as follows [14]:

$$En^{ch} = \sum_i n_i HHV_i \quad (6)$$

Where:

- HHV_i : is the higher heating value of the gas component i (kJ/kmol)

2.2 Exergy of Syngas

The total exergy of a flow gas can be written as the sum of various exergy of the flow gas as follows [18,14]:

$$Ex = Ex^{ki} + Ex^{po} + Ex^{ph} + Ex^{ch} \quad (7)$$

Where:

- Ex : is the total exergy of the gas stream (kJ/kg)
- Ex^{ki} : is the kinetic exergy of the gas stream (kJ/kg)
- Ex^{po} : is the potential exergy of the gas stream (kJ/kg)
- Ex^{ph} : is the physical exergy of the gas stream (kJ/kg)
- Ex^{ch} : is the chemical exergy of the gas stream (kJ/kg)

Since the kinetic exergy and potential exergy represent very small amounts (0.000002-0.007% and 0.00002-0.009%, respectively) of the total exergy, they can be neglected [15]. Thus, equation (7) can then be simplified to:

$$Ex = Ex^{ph} + Ex^{ch} \quad (8)$$

The physical exergy of syngas is calculated as follows [21]:

$$Ex^{ph} = \sum_i n_i [(h - h_0) - T_0(s - s_0)] \quad (9)$$

Where:

- s is the specific entropy of gas component i at the arbitrary temperature (kJ/kmol K)
- s_0 is the specific entropy of gas component i at the environmental state (kJ/kmol K)

Based on the specific enthalpy of N_2 , O_2 , H_2 , CO , CO_2 , CH_4 , C_2H_4 and C_2H_6 at the environmental state shown in Table 1, the specific entropy of gases at arbitrary temperatures can also be obtained as follows [17]:

$$s = s_0 + \int_{T_0}^T \frac{c_p}{T} dT - R \ln \frac{P}{P_0} \quad (10)$$

Where:

- R is the universal gas constant (8.314472 kJ/kmol K)
- P is the pressure of gas component i at the arbitrary state (Pa)
- P_0 is the pressure of the gas i at the environmental state (Pa)

The chemical exergy of syngas is calculated as follows [21]:

$$Ex^{ch} = \sum_i n_i \left(ex_i^{ch} + RT_0 \ln \frac{n_i}{\sum n_i} \right) \quad (11)$$

Where:

- ex_i^{ch} is the standard chemical exergy of gas component i as shown in Table 1 (kJ/kmol)

3. MATERIALS AND METHODS

3.1 Experimental Apparatus

Fig. 1 shows a schematic of the fluidized bed gasification system used in this study. It is a further development of a spout-fluidized bed in which a bubbling fluidized bed is maintained towards the outer region of the bed while the active spout is maintained at the center. The basic physical difference between

the two is the presence of a secondary distributor plate in the spout (above the secondary column). By virtue of its design, the dual distributor fluidized bed ensures a more homogeneous mixture of biomass bed materials since the biomass is pneumatically introduced through the bottom center of the reactor by the secondary column. The uniform biomass distribution in the dual distributor fluidized bed is assured by the spout which entrains bed particles from the bottom of the bed, mixing them with biomass and secondary air and then transporting the mixture to the upper region of the bed. From here, bed particles and the unreacted biomass proceed in a three dimensional fashion; their direction is determined by the movement of bubbles in the bed. The systematic pattern of solids movement gives rise to a unique hydrodynamic system which is more suitable for the gasification of low density biomass materials compared to other conventional fluid-solid configurations.

The fluidized bed gasifier was made of 8 mm thick, 310 stainless steel cylinders of 255mm diameter and 2700mm total height. The primary air (for fluidization), secondary air (for feeding) and the air required for the afterburner are supplied to the fluidized bed reactor by two identical air supply units. Each unit consisted of a blower, a pressure gauge having a pressure range of 0-690kPa, a main valve to control the air flow rate, a by-pass valve to prevent overheating of the electric motor, a steel pipe having an inner diameter of 50mm and a flow meter. The blower (Model GENAIR R4310A-2, Benton Harbour, Michigan, USA) is driven by a 4.8hp (three-phase 220 volts and 13.4 amps) electric motor (Baldor Industrial Motor, Benton Harbour, Michigan, USA) and had a maximum flow capacity of 4.87m³/min and maximum pressure of 20kPa. Each blower inlet had a filter with a micron rating of 25 and a maximum flow of 7.08m³/min to clean the incoming air of contaminants such as dust particles and water. Flow Cell Bypass Flow meters (Metal FLT-type, Cat. No. N-03251-60, Cole Parnar, Chicago, Illinois, USA) were used to measure the air supply rates. Each flow meter was accurate to 2.5% of full scale and could be used up to maximum temperature and pressure of 60°C and 1035kPa, respectively.

An enlarged disengagement section mounted on the top of the main fluidization column was used to reduce the elutriation rate from the fluidized bed. The height of the enlarged section was 395mm whereas the bottom and top diameters

were 255 and 355mm, respectively. The angle of inclination was 30°C from the vertical axis. A cyclone was connected to the exit of the disengagement section to capture the solid particles (dust, ash and char) escaping from the bed. The fluidization column and cyclone were insulated using a flexible blanket (Inswool-HP Blanket, A. P. Green Industries Inc., New Mexico, Missouri, USA) to reduce heat loss from the system. The gas leaves the cyclone through a stainless steel pipe of 150mm inside diameter to the combustion chamber of an afterburner.

3.2 Gas Sampling System

Fig. 2 shows the gas sampling system used in this study. It is consisted of a gas sampling probe, copper tubing, a three-way switch valve, a gas purifier, a compressed air line, a peristolic pump, a sampling bulb, a pressure relief valve, a pressure gauge, a syringe and evacuated tubes. Stainless steel gas sampling probes (each with a cooling jacket) were designed and manufactured. Each probe was 1.27cm in diameter and 45.5cm in length. The diameter of the sampling tube placed inside the probe was 0.64cm. The gas sampling probe was located at the exit of the cyclone. A Masterflex peristolic pump (Cat. No.

N-07567-70, Cole Parmer, Chicago, Illinois, USA) was used to draw the gas from the gasifier and compress it into the gas sampling bulb. The gas sampling bulbs (Cat. No. N-06650-40, Cole Parmer, Chicago, Illinois, USA) could store 0.25L of gas sample at 100 kPa maximum gauge pressure. In order to maintain the gas pressure at the desired level inside the gas sampling bulbs, an adjustable relief valve (Cat. No. SS-4-CPA-3, Nupro Company, Willoughby, Ohio, USA) and a pressure gauge having a pressure range of 0-200kPa (P0121BP, Invensys Systems, Inc., Houston, Texas, USA) were mounted at the exit of the gas sampling bulbs. A syringe and evacuated tube assembly was used to collect the gas sample from the gas sampling bulb. Vacutainer evacuated tubes, having a volume of 10mL each (Co. Model 6430, Becton Dickinson, Franklin Lakes, New Jersey, USA), were used to store the gas samples. These tubes were initially evacuated by the manufacturer up to 80% by volume. They were re-evacuated up to 98% by volume using a vacuum pump before being used. To remove moisture, tar and impurities from the gas, a gas purifier (Cat. No. N-01418-50, Cole Parmer, Chicago, Illinois, USA) was placed between the gas sampling bulb and the Masterflex peristolic pump.

Table 1. Higher heating value (HHV), standard chemical exergy (ex^{ch}), specific enthalpy (h_0) and specific entropy (s_0) of some gas compounds at standard temperature and pressure (25°C and 1 atm)

Gas	HHV (kJ/kmol) ^a	ex^{ch} (kJ/kmol) ^b	h_0 (kJ/kmol) ^a	s_0 (kJ/kmolK) ^a
N ₂	0	720	8669	191.502
O ₂	0	3970	8682	205.033
H ₂	285840	236100	8468	130.574
CO	282990	275100	8669	197.543
CO ₂	0	19870	9364	213.685
CH ₄	890360	831650	—	—
C ₂ H ₄	1408400	1361100	—	—
C ₂ H ₆	1556100	1495840	—	—

^a=[19]; ^b=[20]

Table 2. Coefficients of constant pressure specific heat capacity of some gases [19]

Gas	a	b ($\times 10^{-2}$)	c ($\times 10^{-5}$)	d ($\times 10^{-9}$)	Temperature range(K)
N ₂	28.90	-0.1571	0.8081	-2.8730	273–1800
O ₂	25.48	1.5200	-0.7155	1.3120	273–1800
H ₂	29.11	-0.1916	0.4003	-0.8704	273–1800
CO	28.16	0.1675	0.5327	-2.2220	273–1800
CO ₂	22.26	5.9810	-3.5010	7.4690	273–1800
CH ₄	19.89	5.0240	1.2690	-11.010	273–1500
C ₂ H ₄	3.95	15.640	-8.3440	17.670	273–1500
C ₂ H ₆	6.90	17.270	-6.4060	7.2850	273–1500

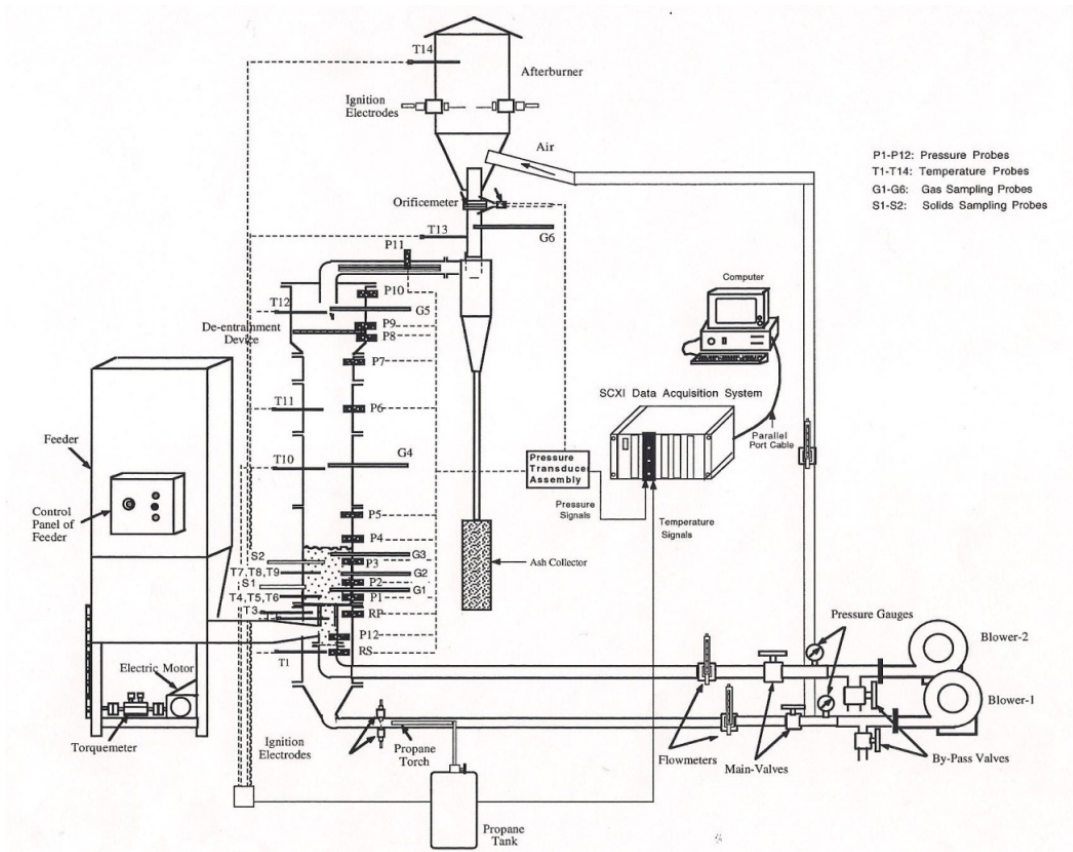


Fig. 1. Schematic diagram of the dual-distributor type fluidized bed gasifier and associated equipment

3.3 Data Acquisition System

A microcomputer and a data acquisition system were used to record and display the measured temperature values. An analog/digital conversion card (Cat. No. N-08109-25, Cole Parmer, Chicago, Illinois, USA) was used together with two thermocouple Amplifier-Multiplexers (Cat. No. N-08109-00, Cole Parmer, Chicago, Illinois, USA). The thermocouple Amplifier-Multiplexers, which each can read up to six thermocouples, provided cold-junction compensation and permitted resolution of thermocouple inputs up to $\pm 0.1^\circ\text{C}$. The data logging software (Cat. No. N-08109-32, Cole Parmer, Chicago, Illinois, USA) which could read 16 inputs in one second was modified and used to display the temperature and feed rate values on the screen and store data on a diskette.

3.4 Biomass Material

Winter wheat straw (Monopol) was collected from a field located in Dyke View Farms Limited (Port

Williams, Nova Scotia, Canada) in the form of small rectangular bales (46 cm \times 48cm \times 70 cm). In order to obtain consistent moisture content of the feedstock, the straw bales were dried in a specially designed bale drying unit to a moisture content of 10-11%. Bales of dried straw were chopped using a specially designed straw chopper to an average size of 1.5 cm. Some properties of the chopped straw are given in Table 3.

3.5 Bed Material

Alumina sand was used as an inert bed material in the fluidized bed gasifier in order to avoid the agglomeration problems encountered in previous experiments with silica sand. It was obtained from Diamonite Products Limited, Ohio, USA. The alumina sand used in this study was kiln fired at 1500°C and very spherical in shape. The main characteristics and chemical composition of the alumina sand is given in Table 4.

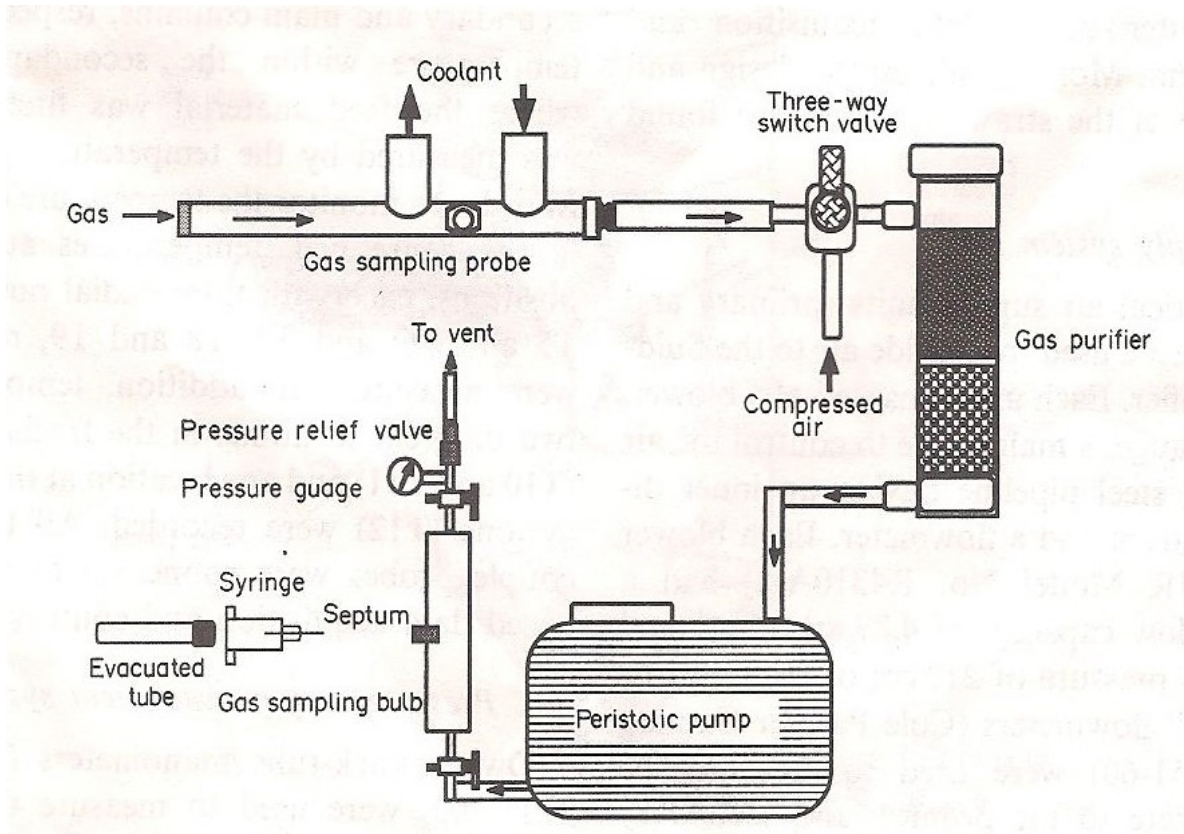


Fig. 2. The gas sampling system

Table 3. Mean characteristics of wheat straw

Characteristics	Value	Unit
Moisture content	10-11	%
Average particle size	1.5×2×0.3	mm
Bulk density	75-80	kg/m ³
Lower heating value	18.71	MJ/kg
Proximate analysis^a		
Volatile mater	78.80	%
Fixed carbon	17.61	%
Ash	3.59	%
Ultimate analysis^a		
C	45.97	%
H	5.75	%
O	44.15	%
N	0.55	%
S	0.12	%
Cl	0.05	%
Ash	3.41	%

^aWeight percentage on dry basis

Table 4. Mean characteristics of the alumina sand

Characteristics	Value	Unit
Particle density	3450	kg/m ³
Bulk density	2000	kg/m ³
Maximum particle size	500	µm
Mean particle size	380	µm
Minimum particle size	300	µm
Minimum fluidization velocity ^a	0.15	m/s
Chemical composition		
Alumina (Al ₂ O ₃)	85.0-90.0	%
Silica (SiO ₂)	8.0-10.0	%
Calcium (CaO)	0.5-2.0	%
Magnesia (MgO)	0.5-1.5	%
Soda (Na ₂ O)	0.1-0.4	%
Iron Oxide (Fe ₂ O ₃)	0.1-0.3	%
Titania (TiO ₂)	0.05-0.15	%
Potash (K ₂ O)	0.01-0.05	%

^aCalculated for ambient conditions

3.6 Experimental Design

The effects of fluidization velocity (0.28, 0.33 and 0.37m/s) and equivalence ratio (0.17, 0.20, 0.25 and 0.35) on the energy and exergy of syngas were investigated. The fluidization velocity (FV) was controlled by altering the primary air supply rate through the main distributor plate. The equivalence ratio (ER) was defined as the ratio of actual air-fuel to stoichiometric air-fuel. It was varied by varying the primary air supply rate through the main distributor plate. The flow rates of feedstock and air at various equivalence ratio-fluidization velocity combinations are given in Table 5.

3.7 Experimental Protocol

A specially designed feeder for wheat straw was used to feed the biomass material into the gasifier. The feeder was filled with a known weight of chopped straw. The alumina sand was placed into the reactor to a bed height of 25.5cm. The primary air supply was turned on to fluidize the sand particles in the main fluidization column and the air flow rate was adjusted to 0.56m³/min (0.67kg/min). The temperature of the bed material was raised to 600°C by combusting the propane-air mixture. The start-up system was then shut down while keeping the primary air supply on to cool the bottom section (wind-box) of the gasifier before starting to feed the straw. The computer-based data acquisition system was activated to monitor and record the temperature and feed rate values.

When the temperature in the secondary column reached 500°C, the secondary air supply was

turned on and adjusted to the minimum rate (0.56kg/min) required to carry the sand particles from the secondary column into the main column. The feeder was turned on and the feed rate was adjusted to allow excess air in order to achieve complete combustion of straw. The bed temperature increased rapidly (to 750°C) by the energy released from the combustion of straw. The fuel feed rate and air flow rates were adjusted to the desired respective levels and the system was operated under this condition for half an hour to insure that the steady state condition was reached in the fluidized bed. Gas samples were then collected during a period of 5 min. When sampling and data recording were completed, the feeder, secondary air supply and primary air supply were shut down. The ash collector was replaced by an empty ash collector. The same procedure was followed at all equivalence ratio-fluidization velocity combinations.

3.8 Gas Sampling and Analysis

The gas sampling procedure was initiated by purging the line and the gas sampling probe with compressed air (550kPa). Using the three-way switch valve, the gas sampling probe was disconnected from the compressed air line and connected to the sampling line. The peristaltic pump was turned on to draw the gas from the gasifier through the gas sampling probe and compress it into the gas sampling bulb. The valve at the exit of the sampling bulb was kept open for three minutes in order to flush the sampling bulb with fresh gas from the gasifier. The valve was closed and the sampling bulb was

filled with the gas sample. The gas sample was collected in an evacuated tube using a syringe. The tube was kept in position for about one minute to allow it to be filled with the gas from the sampling bulb. All the gases were analysed using a gas chromatograph (Hewlett Packard Model 5890 Series II Gas Chromatograph, GMI, Inc., Ramsey, Minnesota, USA). Argon was used as the carrier gas, so as to be able to detect hydrogen besides the other gas components.

Table 5. Flow rates of wheat straw and air

FV(m/s)	ER	Wheat straw (kg/min)	Air(m ³ /min)
0.28	0.17	1.16	1.00
	0.20	0.95	1.00
	0.25	0.76	1.00
	0.35	0.54	1.00
0.33	0.17	1.37	1.17
	0.20	1.14	1.17
	0.25	0.91	1.17
	0.35	0.65	1.17
0.37	0.17	1.55	1.33
	0.20	1.29	1.33
	0.25	1.04	1.33
	0.35	0.75	1.33

4. RESULTS AND DISCUSSION

4.1 Mean Temperature of the Bed

The mean temperatures of the dense bed in the gasifier, where gasification reactions take place, are shown in Table 6. When the FV was increased from 0.28 to 0.37 (32.14%), the mean temperature increased from 649°C to 677°C (4.31%), from 685°C to 732°C (6.86%), from 782°C to 820°C (4.86%) and from 848°C to 875°C (3.18%) at the ERs of 0.17, 0.20, 0.25 and 0.35, respectively. However, when the ER was increased from 0.17 to 0.35 (105.88%), the mean temperature increased from 661°C to 875°C (32.38%), from 649°C to 848°C (30.66%) and from 677°C to 875°C (29.25%) for the FVs of 0.28, 0.33 and 0.37m/s, respectively. The results obtained from this study showed that the effect of the ER on the gasification temperature (29.25-32.38%) was much greater than that of the FV (3.18-6.86%).

The results showed that higher FV achieved a better mixing of the feed material with bed material and thus resulted in a better heat transfer and higher temperatures. Sharma et al. [22] and Ergudenler and Ghaly [23] stated that

higher FV can breakdown segregated lumps and remove in-bed channels, resulting in a better particle mixing. Mandal et al. [24] stated that packed fluidized bed may result in better heat transfer. Mansaray et al. [25] stated that the increased air, resulted from the increase in FV, increased the rate of exothermic reactions and raised the temperature of the bed.

Increasing the ER provided more air and resulted in a faster ignition and higher temperatures. Lickrastina et al. [26] stated that increasing ER resulted in a faster gasification of wheat straw and a faster ignition of the volatiles with pronounced increase in the temperature to its peak value. Zhao et al. [27] stated that increase in ER is favorable for the cracking reactions of heavy hydrocarbons, which can also increase the gasification temperatures.

4.2 Compositions of Syngas

The compositions of the syngas produced at various FVs and ERs are shown in Table 6. The gas components CO, H₂, N₂, CO₂, CH₄, C₂H₄ and C₂H₆ varied within the ranges of 11.13-18.35, 1.84-6.38, 27.70-56.44, 8.85-14.37, 2.12-3.91, 0.84-2.33 and 0.00-0.28mol/kg fuel, respectively. Generally, increasing the FV decreased the yield of CO₂ and initially increased the yields of H₂, CH₄ and C₂H₄ which then decreased with further increases in the FV. However, the FV showed no obvious effect on the yields of N₂, CO₂ and C₂H₆. Several researchers reported similar variation of gas components as a result of variations in the FV. Mansaray et al. [25] stated that increasing FV could increase the concentrations of N₂ and CO₂. Sadaka et al. [28] and Mansaray et al. [25] stated that increasing FV could decrease the mole fractions of CO, H₂, CH₄, C₂H₄ and C₂H₆.

The results also showed that increasing the ER increased the yields of CO, H₂, N₂, CO₂ and C₂H₄ and initially increased the yields of CH₄ and C₂H₆ which then decreased with further increases in the ER. Yoon et al. [29] stated that increases in ER can boost the oxidation reaction which supports the endothermic gasification reactions. Ergudenler and Ghaly [23] stated that ER affected the gas compositions significantly, but the effect of FV was minimal.

4.3 HHV of Syngas

The HHVs of syngas produced at various FVs and ERs are shown in Table 6. When the FV

increased from 0.28 to 0.37 (32.14%), the HHVs of syngas fluctuated in the ranges of 5.33-6.03 (13.13%), 6.19-6.59 (6.46%), 6.31-7.29 (15.53%) and 5.23-6.33 (21.03%) MJ/Nm³ at the ERs of 0.17, 0.20, 0.25 and 0.35, respectively. It appears that increasing the FV increased the amount of oxygen thereby increased the oxidation of combustible gases and decreased the HHV of syngas. Mansaray et al. [25] stated that lower HHV of syngas was obtained at higher FV when higher concentrations of products were caused by the increase of the air flow rate. Sadaka et al. [28] stated that increases in the FV decreased the HHV of syngas as there were decreases in the combustible gases and increase in N₂. However, Ergudenler and Ghaly [23] stated that the effect of FV on the HHV of the syngas was dependent on the ER.

When the ER increased from 0.17 to 0.35 (105.88%), the HHVs of syngas increased first and then declined within the ranges of 5.56-7.29 (31.12%), 5.07-6.31 (24.46%) and 5.98-6.48 (8.36%) MJ/Nm³ at the FVs of 0.28, 0.33 and 0.37m/s, respectively. The results obtained from this study showed that ER was more influential than FV on the HHV of syngas. The results showed that a lower ER resulted in a higher HHV and a higher ER decreased the combustible gases and reduced the HHV of syngas. Lickrastina et al. [26] stated that increases in the ER can enhance the transition from the heating/drying phase to the devolatilization stage, thus resulting in a faster gasification. Yoon et al. [29] stated that increases in ER can boost the oxidation reaction which supports the endothermic gasification reactions. However, Karmakar et al. [30], Yoon et al. [29] and Mansaray et al. [25] stated that a higher ER will decrease the concentrations of H₂ and CO and degrade the gas quality with more N₂ dilution and higher CO₂ concentration due to oxidization of larger fraction of carbon in feedstock.

4.4 Energy Values of Syngas

The energy values and distributions of gas components at various FVs and ERs are shown in Table 7. The energy values of CO, H₂, N₂, CO₂, CH₄, C₂H₄ and C₂H₆ varied within the ranges of 3466.27-5790.62, 570.34-2025.86, 774.42-1973.99, 343.22-726.34, 1970.30-3694.93, 1225.03-3453.06 and 0.00-456.65 kJ/kg fuel, respectively. Although different gas components contributed differently to the total energy of syngas, the overall distribution was CO>CH₄>C₂H₄>(H₂& N₂)>(CO₂& C₂H₆). Zhang et

al. [14] stated that the energy value of gas component is determined by the temperature of the bed and the yield of the gas component. Equation (3) shows that both the increases in enthalpy and yield can result in increases in the physical energy of gas component. Also, equation (6) shows that the increase in yield can lead to increases in the chemical energy of gas component.

The effects of FV and ER on the total energy of syngas are show in Fig. 3. When the FV was increased from 0.28 to 0.37 (32.14%), the total energy of syngas decreased first and then increased. The variations were within the ranges of 8844.61-9694.72 (9.61%), 11474.15-12380.52 (7.90%), 13530.95-16210.50 (19.80%) and 14312.15-16861.89 (17.82%)kJ/kg fuel at the ERs of 0.17, 0.20, 0.25 and 0.35, respectively. Zhang et al. [14] stated that the energy value of the gas component is determined by the temperature of the bed and the yield of the gas component. The initial decreases in the energy values were due to the decreases in the yields of CO, H₂ and C₂H₄ whereas the later increases in the energy values were resulted from the increases in the yields of CO, H₂, CH₄ and C₂H₄. However, when the ER was increased from 0.17 to 0.35 (105.88%), the total energy of syngas increased from 9488.79 to 16861.89 (77.70%), from 8844.61 to 14312.15 (61.82%) and from 9694.72 to 16578.35 (71.00%)kJ/kg fuel for the FVs of 0.28, 0.33 and 0.37m/s, respectively. The results obtained from this study showed that the effect of the ER on the total energy of syngas (61.82-77.70%) was much greater than that of the FV (7.90-19.80%). Zhao et al. [27] stated that ER is a crucial factor affecting the performance of biomass gasification. Sharma et al. [22] stated that FV plays a key role in the gasification process and influences the gasifier performance in terms of gas composition and yield. Ergudenler and Ghaly [23], Mansaray et al. [25] and Sadaka et al. [28] stated that ER affected the gas composition significantly but the effect of FV was minimal.

4.5 Exergy Values of Syngas

Table 8 shows the exergy values of gas components at various FVs and ERs. The exergy values of CO, H₂, N₂, CO₂, CH₄, C₂H₄ and C₂H₆ varied within the ranges of 3123.99-5200.75, 433.63-1548.33, 224.62-751.35, 262.97-751.35, 1780.38-3327.70, 1151.65-3237.09 and 0.00-425.11 kJ/kg fuel, respectively. These values were determined by the temperature of the bed

and the yield of the gas component [14]. Equation (9) shows that the increases in enthalpy and entropy can result in increases in the physical exergy of gas component, while the increase in the yield of gas component can lead

to increases in the physical exergy. Also, equation (11) shows that increases in the yield of gas component can result in increases in its chemical exergy.

Table 6. Bed temperatures, syngas compositions and HHVs

FV (m/s)	ER	Temperature (°C)	Gas components (mol/kg fuel)							HHV (MJ/Nm ³)
			CO	H ₂	N ₂	CO ₂	CH ₄	C ₂ H ₄	C ₂ H ₆	
0.28	0.17	661	12.59	2.22	27.70	8.85	2.27	0.92	0.24	6.03
	0.20	685	15.59	3.14	32.38	10.10	3.05	1.37	0.27	6.59
	0.25	782	18.35	5.34	37.58	10.82	3.88	2.17	0.28	7.29
	0.35	875	18.21	6.38	56.44	14.37	3.82	2.33	n.a.	5.56
0.33	0.17	649	11.65	1.84	29.92	9.18	2.12	0.84	0.20	5.33
	0.20	693	13.94	2.83	32.12	9.49	2.93	1.22	0.28	6.26
	0.25	820	14.51	5.16	37.99	10.33	3.23	1.68	0.16	6.31
	0.35	848	15.31	4.82	54.39	12.77	3.17	1.85	0.16	5.07
0.37	0.17	677	11.13	2.73	28.15	9.98	2.59	0.99	0.24	5.98
	0.20	732	13.62	3.61	34.23	8.96	3.06	1.37	0.22	6.19
	0.25	805	14.30	5.39	36.71	9.90	3.34	1.67	0.19	6.48
	0.35	875	17.80	5.82	47.50	12.80	3.91	2.19	0.16	6.23

FV= the fluidization velocity; ER= the equivalence ratio; HHV = the higher heating value of syngas and n.a.= not applicable

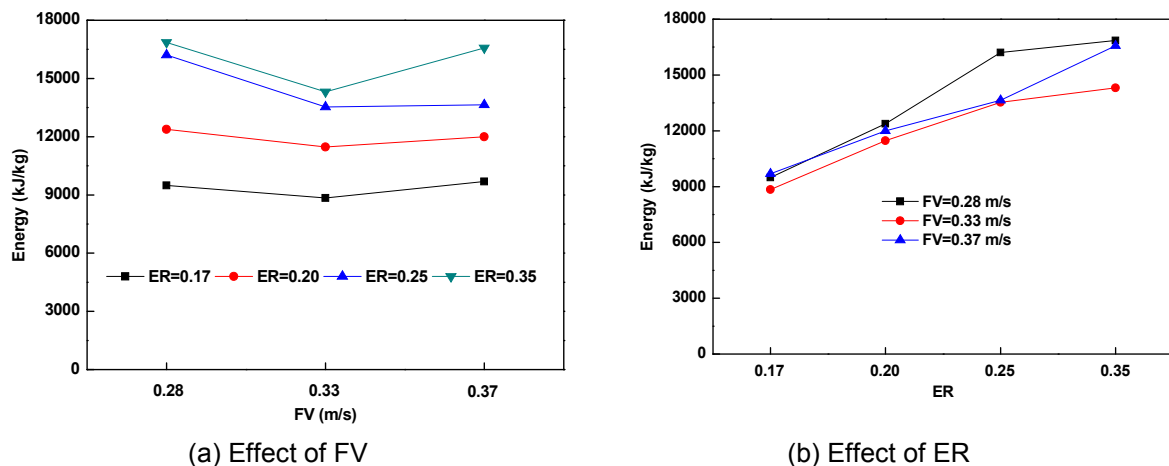


Fig. 3. Effects of FV and ER on the syngas energy

The results showed that the exergy values of the gas components were lower than their corresponding energy values. This is because: (a) the physical exergy of a gas component is lower than the corresponding physical energy as shown in equations (3) and (9) and (b) the chemical exergy values of combustible gases are lower than the corresponding chemical energy values (HHVs) as shown in Table 1. Similar results were reported by Karamarkovic and Karamarkovic [31] for a typical biomass represented by $\text{CH}_{1.4}\text{O}_{0.59}\text{N}_{0.0017}$, by Sreejith et al. [32] for four biomass fuels and by Zhang et al. [14] for three biomass fuels.

Although different gas components contributed differently to the total exergy of the syngas (Table 8), the overall distribution was $\text{CO} > \text{CH}_4 > \text{C}_2\text{H}_4 > \text{H}_2 > (\text{C}_2\text{H}_6 \text{ \& \; } \text{CO}_2 \text{ \& \; } \text{N}_2)$. This is different from the energy distribution of $\text{CO} > \text{CH}_4 > \text{C}_2\text{H}_4 > (\text{H}_2 \text{ \& \; } \text{N}_2) > (\text{CO}_2 \text{ \& \; } \text{C}_2\text{H}_6)$ for the gas components, because different gases have different chemical energy/exergy ratios as reported by Moran et al. [20]. Zhang et al. [14] stated that the chemical/physical energy ratios of product gases varied in the range of 2.16-5.20 whereas the chemical/physical exergy ratios varied in the range of 4.50-13.45. These differences can affect the contribution of different gas components to the energy and exergy of syngas.

Table 7. Energy values and distribution of gas components

FV(m/s)	ER	Energy values (kJ/kg fuel)							Energy distribution
		CO	H ₂	N ₂	CO ₂	CH ₄	C ₂ H ₄	C ₂ H ₆	
0.28	0.17	3912.35	691.27	774.42	343.22	2114.20	1339.77	391.86	CO>CH ₄ >C ₂ H ₄ >N ₂ >H ₂ >C ₂ H ₆ >CO ₂
	0.20	4857.36	977.81	930.25	404.75	2843.95	2010.90	440.13	CO>CH ₄ >C ₂ H ₄ >H ₂ >N ₂ >C ₂ H ₆ >CO ₂
	0.25	5776.24	1680.36	1198.58	491.06	3643.39	3193.08	450.09	CO>CH ₄ >C ₂ H ₄ >H ₂ >N ₂ >CO ₂ >C ₂ H ₆
	0.35	5790.62	2025.86	1973.99	726.34	3608.55	3453.06	0.00	CO>CH ₄ >C ₂ H ₄ >H ₂ >N ₂ >CO ₂ >C ₂ H ₆
0.33	0.17	3615.57	570.34	825.01	350.46	1970.30	1225.03	321.56	CO>CH ₄ >C ₂ H ₄ >N ₂ >H ₂ >CO ₂ >C ₂ H ₆
	0.20	4348.75	883.80	931.34	384.43	2731.68	1785.07	456.65	CO>CH ₄ >C ₂ H ₄ >N ₂ >H ₂ >C ₂ H ₆ >CO ₂
	0.25	4587.13	1629.99	1259.37	490.45	3044.58	2479.13	266.02	CO>CH ₄ >C ₂ H ₄ >H ₂ >N ₂ >CO ₂ >C ₂ H ₆
	0.35	4856.03	1526.58	1853.31	626.53	2986.64	2730.43	263.45	CO>CH ₄ >C ₂ H ₄ >N ₂ >H ₂ >CO ₂ >C ₂ H ₆
0.37	0.17	3466.27	849.32	801.51	395.98	2409.28	1447.87	392.75	CO>CH ₄ >C ₂ H ₄ >H ₂ >N ₂ >CO ₂ >C ₂ H ₆
	0.20	4265.78	1129.68	1035.78	382.08	2861.41	2004.90	360.30	CO>CH ₄ >C ₂ H ₄ >H ₂ >N ₂ >CO ₂ >C ₂ H ₆
	0.25	4512.86	1699.64	1198.66	461.76	3140.93	2468.10	310.21	CO>CH ₄ >C ₂ H ₄ >H ₂ >N ₂ >CO ₂ >C ₂ H ₆
	0.35	5661.08	1846.87	1661.41	646.97	3694.93	3251.85	270.27	CO>CH ₄ >C ₂ H ₄ >H ₂ >N ₂ >CO ₂ >C ₂ H ₆

Table 8. Exergy values of syngas components

FV(m/s)	ER	Gas components (mol/kg fuel)							Exergy distribution
		CO	H ₂	N ₂	CO ₂	CH ₄	C ₂ H ₄	C ₂ H ₆	
0.28	0.17	3532.03	526.74	224.62	262.97	1910.57	1259.52	365.02	CO>CH ₄ >C ₂ H ₄ >H ₂ >C ₂ H ₆ >CO ₂ >N ₂
	0.20	4383.63	746.14	277.37	307.72	2569.75	1890.43	409.75	CO>CH ₄ >C ₂ H ₄ >H ₂ >C ₂ H ₆ >CO ₂ >N ₂
	0.25	5200.75	1286.06	403.28	367.31	3287.32	2998.58	418.17	CO>CH ₄ >C ₂ H ₄ >H ₂ >C ₂ H ₆ >N ₂ >CO ₂
	0.35	5191.37	1548.33	751.35	542.31	3248.50	3237.09	0.00	CO>CH ₄ >C ₂ H ₄ >H ₂ >N ₂ >CO ₂ >C ₂ H ₆
0.33	0.17	3261.95	433.63	238.16	269.15	1780.38	1151.65	299.50	CO>CH ₄ >C ₂ H ₄ >H ₂ >C ₂ H ₆ >CO ₂ >N ₂
	0.20	3921.18	673.88	283.07	291.33	2467.90	1677.64	425.11	CO>CH ₄ >C ₂ H ₄ >H ₂ >C ₂ H ₆ >CO ₂ >N ₂
	0.25	4120.72	1247.64	449.22	366.76	2744.44	2325.98	246.80	CO>CH ₄ >C ₂ H ₄ >H ₂ >N ₂ >CO ₂ >C ₂ H ₆
	0.35	4352.59	1164.58	695.18	467.12	2688.96	2560.01	244.20	CO>CH ₄ >C ₂ H ₄ >H ₂ >N ₂ >CO ₂ >C ₂ H ₆
0.37	0.17	3123.99	648.29	237.63	305.08	2177.27	1360.90	365.73	CO>CH ₄ >C ₂ H ₄ >H ₂ >C ₂ H ₆ >CO ₂ >N ₂
	0.20	3840.40	862.82	333.20	286.07	2583.32	1883.25	335.01	CO>CH ₄ >C ₂ H ₄ >H ₂ >C ₂ H ₆ >N ₂ >CO ₂
	0.25	4055.15	1301.79	418.84	344.74	2832.32	2316.19	287.95	CO>CH ₄ >C ₂ H ₄ >H ₂ >N ₂ >CO ₂ >C ₂ H ₆
	0.35	5079.73	1412.00	626.71	483.32	3327.70	3048.82	250.44	CO>CH ₄ >C ₂ H ₄ >H ₂ >N ₂ >CO ₂ >C ₂ H ₆

Fig. 4 shows the effects of FV and ER on the total exergy of syngas. When the FV was increased from 0.28 to 0.37 (32.14%), the total exergy of the syngas decreased first and then increased. The variations were within the ranges of 7437.46-8219.78 (10.52%), 9744.29-10584.70 (8.62%), 11504.99-13961.66 (21.35%) and 12187.09-14532.49 (19.25%) kJ/kg fuel at the ERs of 0.17, 0.20, 0.25 and 0.35, respectively. Zhang et al. [14] stated that the exergy value of gas component is determined by the temperature of the bed and the yield of the gas component. The initial decreases in the exergy values were caused by the decreases in the yields of CO, H₂ and C₂H₄ whereas the later increases in the exergy values were resulted from the increases in the yields of CO, H₂, CH₄ and C₂H₄. However, when the ER was increased from 0.17 to 0.35 (105.88%), the total exergy of the syngas increased from 8081.29 to 14532.49 (79.83%), from 7437.46 to 12187.09 (63.86%) and from 8219.78 to 14235.44 (73.19%) kJ/kg fuel for the FVs of 0.28, 0.33 and 0.37 m/s, respectively. The

results obtained from this study showed that the effect of the ER on the total exergy of syngas (63.86-79.83%) was much greater than that of the FV (8.62-21.35%).

Prins et al. [33] stated that the energy and exergy contained in syngas exhibit maximum values at a critical ER where all carbon in biomass fuel is consumed. Before reaching the optimum ER, the energy and exergy of syngas increase when ER is increased due to the conversion of solid carbon. However, beyond this maximum ER, the energy and exergy decrease because the decreases in chemical energy and exergy are not fully compensated for by the increases in the physical energy and exergy. Zhang et al. [14] stated that the critical ER is dependent on the composition of biomass fuel. The results obtained from this study showed that the highest energy (16861.89 kJ/kg fuel) and exergy (14532.49 kJ/kg fuel) of syngas were achieved at the ER of 0.35 and the FV of 0.28m/s.

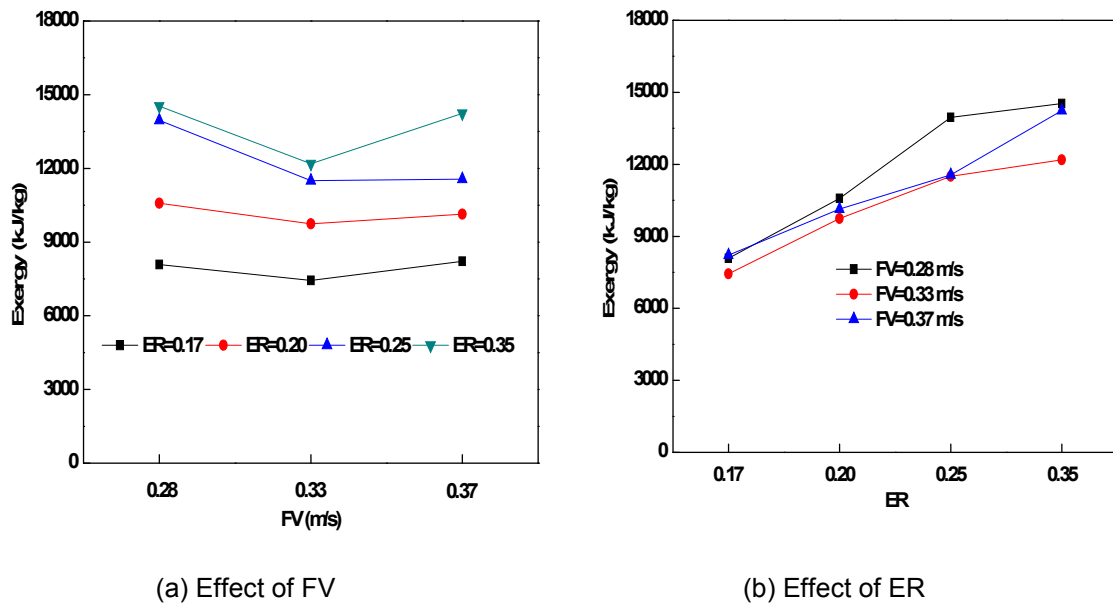


Fig. 4. Effects of FV and ER on the exergy value of syngas

5. CONCLUSIONS

The energy and exergy of syngas from the gasification of wheat straw in a dual-distributor type fluidized bed gasifier were evaluated at various FVs and ERs. The energy values of CO, H₂, N₂, CO₂, CH₄, C₂H₄ and C₂H₆ varied within the ranges of 3466.27-5790.62, 570.34-2025.86, 774.42-1973.99, 343.22-726.34, 1970.30-3694.93, 1225.03-3453.06 and 0.00-456.65

kJ/kg fuel, respectively. The overall energy distribution was CO>CH₄>C₂H₄>(H₂&N₂)>(CO₂&C₂H₆). The results showed that increasing the FV from 0.28 to 0.37 (32.14%), initially decreased the total energy of syngas and then increased it, resulting in a net increase of 7.90-19.80% depending on the ER used. However, when the ER was increased from 0.17 to 0.35 (105.88%), the total energy of syngas increased by 61.82-77.70% depending on the FV used. The effect of the ER on the total energy of syngas was much

greater than that of the FV. The exergy values of CO, H₂, N₂, CO₂, CH₄, C₂H₄ and C₂H₆ varied within the ranges of 3123.99-5200.75, 433.63-1548.33, 224.62-751.35, 262.97-751.35, 1780.38-3327.70, 1151.65-3237.09 and 0.00-425.11 kJ/kg fuel, respectively. The overall exergy distribution was CO>CH₄>C₂H₄>H₂>(C₂H₆& CO₂& N₂). Increasing the FV from 0.28 to 0.37 (32.14%) increased the exergy of the syngas by 8.62-21.35% depending on the ER used. On the other hand, increasing the ER 0.17 to 0.35 (105.88%) increased the total exergy of the syngas by 63.86-79.83% depending on the FV used. The effect of the ER on the total exergy of syngas was also much greater than that of the FV. The results showed that the exergy values of the syngas were lower than their energy values because the gas components contributed differently to the energy and exergy (the physical exergy of gas components are lower than the corresponding physical energy and the chemical exergy of combustible gases are lower than the corresponding chemical energy). The highest energy (16861.89 kJ/kg fuel) and exergy (14532.49 kJ/kg fuel) of syngas were obtained at the FV of 0.28m/s and the ER of 0.35.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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