Comparative Study of Two Small-Scale Downdraft Gasifiers in Terms of Continuous Flammability Duration of Producer Gas from Rice Husk and Sawdust Gasification

A.A.P. Susastriawan*‡, Harwin Saptoadi**‡, Purnomo**

*Doctoral student of Depart. of Mechanical and Industrial Engineering, Faculty of Engineering, Universitas Gadjah Mada, Indonesia
**Depart. of Mechanical and Industrial Engineering, Faculty of Engineering, Universitas Gadjah Mada, Indonesia

(agung589E@akprind.ac.id; harwins@ugm.ac.id; purnomo_tm@yahoo.com)

‡ Corresponding Author; A.A.P. Susastriawan, Depart.of Mechanical Engineering, Institut Sains & Teknologi AKPRIND, Jl. Kalisahak No. 28 Komplek Balapan, Yogyakarta 55222, Indonesia, agung589E@akprind.ac.id
‡ Corresponding Author; Harwin Saptoadi, Depart. of Mechanical and Industrial Engineering, Faculty of Engineering, Universitas Gadjah Mada, Jl. Grafika No.2, DI Yogyakarta 55281, Indonesia, harwins@ugm.ac.id

Received: 02.02.2017 Accepted:03.03.2017

Abstract- In this work, two small scale throat-less downdraft gasifiers (gasifier I & gasifier II) are tested on feedstocks of rice husk and sawdust at different setup. The test aims to compare the two gasifiers in terms of continuous flammability duration of producer gas during one hour batch operation. The result shows that maximum 32 minutes continuous flammability duration is obtained from setup C (Rice husk gasification; primary air at 1st stage tuyer; secondary air induced at top hole of gasifier lid) for the gasifier I and maximum 30 minutes continuous flammability duration is achieved from setup I (Rice husk-sawdust blend gasification, primary air at 5th stage tuyer; gasification initiation at 1st stage tuyer) for the gasifier II. For closed top setup, the gasifier II is more stable than the gasifier I in terms of continuous flammability duration of producer gas, either for rice husk or sawdust gasification. The maximum continuous flammability duration are 6 minutes and 8 minutes for rice husk and sawdust gasification in closed top gasifier I. Meanwhile, it reaches 32 minutes for rice husk gasification and 16 minutes for sawdust gasification in closed top gasifier II.

Keywords- downdraft, gasifier, flammability, duration, producer gas.

1. Introduction

Since combustion of producer gas is cleaner than direct combustion of biomass, gasification technology got more attention for developing biomass conversion energy system [1] and more important in the future [2]. Downdraft gasifier, one of fixed bed gasifiers, is a promising technology for converting biomass waste into combustible gas (producer gas). Low tar content in producer gas and relative simple construction are also the reasons in selection of downdraft gasifier. Downdraft gasifier is more suitable for small-scale applications [3], [4], [5]. Typically, downdraft gasifiers have a capacity of 10 kW–1 MW [6]

In downdraft gasifier, biomass is fed from the top of gasifier and flows downward during gasification. Sequences processes of drying, pyrolysis, oxidation, and reduction occur during gasification as shown in Fig. 1. Typically, temperature in drying zone is about 100-200^{0}C [7]. Conversion of moisture to water vapor occurs during drying process. The conversion takes place due to heat transfer between hot gases from the oxidation zone to biomass in the drying zone. During pyrolysis, biomass molecules are decomposed into condensable gases, tar, and char at temperatures between 200 and 700^{0}C in the absence of oxygen. The condensable gases in turns are decomposed into non-condensable gases (CO, CO_2, H_2, and CH_4), liquid, and char [6]. The decomposition occurs between gas-gas phase (homogeneous reaction) and gas-solid phase (heterogeneous reaction). The condensable vapor is cracked into non-condensable permanent gases (CO and CO_2) [6]. In oxidation zone, partial oxidation as well as total oxidation take place. The oxidation temperature is about 800-1400^{0}C [6]. Partial oxidation of char (C) produces carbon monoxide and heat, while total oxidation of char produces carbon dioxide and more heat. Amount of heat released during total oxidation is three times more than during partial oxidation. Partial oxidation releases 111 kJ/mol heat and total oxidation results 394 kJ/mol heat. Heat released during oxidation is used for drying, pyrolysis, and other endothermic reactions during reduction. Main gasification reactions occur during reduction process [6]. Combustible gases in producer gas are formed during reduction through Bouduard, Water-Gas, Water-Gas Shift, and Methane reaction. For air gasification, the producer gas contains mainly a combustible gases such as CO, H_2, and CH_4 and non-combustible gases such as CO_2 and N_2.

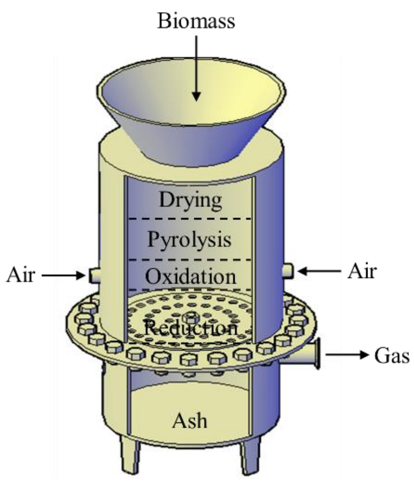


Fig 1. Gasification in downdraft gasifier

The process of drying, pyrolysis, oxidation (partial and total) and reduction (Bouduard, Water-Gas, Water-Gas Shift, and Methane reaction) are formulated as follows [6]:

Drying

$$m_{H_2O(l)} = m_{H_2O(g)} \quad (1)$$

Pyrolysis

$$C_nH_mO_p(Biomass) \xrightarrow{Heat} \Sigma liq\, C_xH_yO_z + \Sigma_{gas} C_aH_bO_c + H_2O + Char \quad (2)$$

Partial oxidation

$$C + \tfrac{1}{2}O_2 \rightarrow CO - 111\ kJ/mol \quad (3)$$

Total oxidation

$$C + O_2 \rightarrow CO_2 - 394\ kJ/mol \quad (4)$$

Bouduard reaction

$$C + CO_2 \rightarrow 2CO + 172\ kJ/mol \quad (5)$$

Water-Gas reaction

$$C + H_2O \rightarrow CO + H_2 + 131\ kJ/mol \quad (6)$$

Water-Gas Shift reaction

$$CO + H_2O \rightarrow CO_2 + H_2 - 41.2\ kJ/mol \quad (7)$$

Methane reaction

$$C + 2H_2 \rightarrow CH_4 - 74.8\ kJ/mol \quad (8)$$

With the use of equation given in [8] and elemental composition of rice husk (33.25% C, 5.11%H, 33.49% O) and sawdust (45.48% C, 5.11% H, 46.38% O) from [9], global gasification reaction of rice husk and sawdust gasification can be written as follows:

Global gasification reaction of rice husk

$$CH_{1.84}O_{0.41} + wH_2O + m(O_2 + 3.76N_2) \rightarrow x_1H_2 + x_2CO + x_3CO_2 + x_4H_2O + x_5CH_4 + 3.76mN_2 \quad (9)$$

Global gasification reaction of sawdust:

$$CH_{1.35}O_{0.57} + wH_2O + m(O_2 + 3.76N_2) \rightarrow x_1H_2 + x_2CO + x_3CO_2 + x_4H_2O + x_5CH_4 + 3.76mN_2 \quad (10)$$

For downdraft gasifier, there is a limitation in the range of biomass size [10]. It has been recognized that small size biomass significantly increases the energy efficiency of gasification process [11]. Small size biomass yields more producer gas than larger size biomass for particular gasification time. Heat transfer area increases with reduction in particle size, hence increases releasing rate of biomass volatile during pyrolysis process [1]. Gasification of small size biomass may have high pressure drop problem as well as high dust content in producer gas. Problem of unsuitable build up gasification bed in the reduction zone was also found as a problem of small size and low density biomass [12]. On the other hand, larger particle size tends to reduce reactivity of biomass feedstock, causing in start up and bridging problem [1] hence reducing production rate of producer gas [13]. Besides, homogeinity of biomass size also affects performance of gasifier. The more homogeneous the size, the more effective the gasification, hence increasing efficiency of gasifiers [14]. Various biomasses have been utilized for feedstock of gasifier, i.e. woody biomass [15], microalgae [16] and [17], Munipical Solid Waste [18], cow dung [19], and many more.

From many downdraft gasifiers have been developed and reported, only a few gasifiers were used for biomass with low density such as rice husk and sawdust. Yoon et al. [20] developed throat-less downdraft gasifier for rice husk and rice husk pellet. For rice husk gasification, feedstock consumption rate and air flow rate were 40-45 kg/h and 60-75 Nm^3/h, respectively. Producer gas has heating value of 1084 $kcal/Nm^3$. The gasifier was coupled to 10 kW gas engine. A 350 kW demonstrative downdraft gasifier for gasification of rice husk and vine pruning was reported by [12]. Amount of feedstock was maintained constant in reactor with level control mechanism. Air was injected above restriction area of reactor. For rice husk gasification, heating value of producer gas was 2.5-3.8 MJ/m^3 at equivalence ratio of 0.4. A bench scale throat-less downdraft gasifier have been designed and tested on rice husk [21]. The gasifier has a diameter of 4 inch and total height of 18 inch. In order to run 10 kW IC engine, it was required rice husk consumption rate of 28 kg/h. Rice husk was also used for feedstock of throat-less downdraft gasifier [22]. At optimum equivalence ratio of 0.211, producer gas heating value and cold gas efficiency were 4.44 MJ/Nm^3 and 80.85%, respectively.

Meanwhile, Wander *et al*. [23] worked on pine sawdust gasification in downdraft gasifier. The gasifier has a capacity of 12 kg/h, internal diameter of 270 mm, and height of 1100 mm. The gasifier was also has additional LPG burner. Channeling and bridging were found as a main problem during sawdust gasification. The problems may due to low density of sawdust. In order to encounter that problems, sawdust was pelletized prior to be used as feedstock of downdraft gasifier. Sawdust pellet was used as feedstock of throat type downdraft gasifier by [24] and [25]. Other work in gasification of agro residue briquette was performed by Pareek *et al* [26]. The gasifier was coupled to power generation system. However, the use of pelletized feedstock resulted high pressure drop and residue fragmented and also required additional processing cost for pelletizing a low density biomass.

Air, steam, and oxygen can be used as gasification agent. Mostly, air is used as gasification agent due to its availability and cost consideration. Important process parameter regarding air gasification is equivalence ratio. Equivalent ratio is defined as a ratio of actual air used in gasification to stoichiometry air [3]. For effective gasification, typically equivalent ratio is in the range of 0.2 to 0.4 [10]. Gasification is dominated by pyrolysis for equivalent ratio lower than 0.2 and on the other hand, gasification is dominated by combustion for equivalent ratio higher than 0.4 [27]. Air as gasification agent is supplied into oxidation zone through air nozzle (tuyer) by means of blower or induced draft fan. In order to enhance performance of gasifier, multi-stage air supply systems have been developed. For example, Galindo *et al*. [28] who developed two stage air supply system (primary and secondary air). Better quality of producer gas is obtained with the use of double stage air. The use of two stage air supply increases pyrolysis temperature. As temperature of pyrolysis zone increases, much lighter compounds are formed during feedstock devolatilization in the pyrolysis zone. The compounds are more easily cracked when entering the combustion zone [28]. Others researchers [29] and [30] reported gasifier with three-stage air supply system. The use of three-stage air supply gave high and uniform temperature in the oxidation and the reduction zones, thus better tar cracking is obtained [29].

For heating application, producer gas is burnt in a burner. Aerated naturally aspirated burner for producer gas has been designed by [31]. Three important parameters have to be considered in designing producer gas burner are producer gas flow rate, pressure different between producer gas and ambient, and buoyancy effect due to relatively high temperature of producer gas entering the burner. Modified premixed LPG burner for producer gas was reported by [32]. The burner can be operated at 30.5–39.4 kW_{th} with thermal efficiency within 84-91% and flame temperature in the range of 1200 ^{0}C - 1260 ^{0}C. The optimum efficiency of the burner was obtained at producer gas flow rate and equivalence ratio of 24.3 Nm^3/h and 0.84, respectively. In order to stabilize the flame, bluff body is used in premixed burner and the burner was tested on open core throat-less downdraft gasifier [33]. The stable and uniform flame was obtained with the use of conventional bluff body with blockage ratio of 0.65 and flammability limit of the burner was established in the range of 40-45%. In more recent work, an integrated biomass gasification-gas turbine system has been modeled by [34]. The model showed that total energy efficiency of the combined cycle was found to be 58.9%.

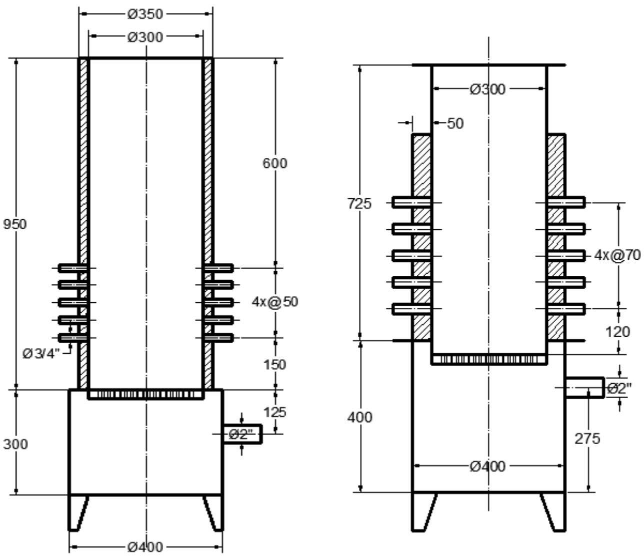
Stability of gasifier can be observed from continuous production of flammable producer gas during gasification process. Flammable producer gas means that generated producer gas from gasification is flammable in the flare. The continuous flammability duration is defined as continuous time of producer gas flaming in the flare. The longer the duration of continuous producer gas flame, the more stable the gasification process. Hence, the continuous flammability duration of producer gas may be used for indication of gasifier stability. The flammability of producer gas is affected by composition of flammable gases in producer gas which in turns the generated flammable gases is dependent on gasification parameters, such as air flow. In downdraft gasifiers with induced draft fan, the air flow is affected by bed porosity, gasifier height, and also capacity of the fan.

In this work, two small-scale throat-less downdraft gasifiers are compared in terms of continuous flammability duration of producer gas flame from rice husk and sawdust gasification. Although the gasifiers are similar type (downdraft type with induced draft fan), but the gasifiers have differences in height, tuyer diameter, and also distance between tuyer-stage as shown in Fig.2. Height, tuyer diameter, and tuyer distance above the grate may have influences on air flow into the reactor. Besides, bed porosity also plays important role in self-regulating nature of induced air in downdraft gasifier. For induced downdraft gasifier, air flow rate to the oxidation zone differs during gasification which is depended on bed porosity and suction fan capacity. The variation of air flow alters heat released during oxidation process thus gasification temperature oscillated [35]. The temperature oscillation affects the stability of gasification process, thus impacts on producer gas flammability. Hence, it is reasonable for conducting this comparative study of the downdraft gasifiers in order to figure out flammability duration of producer gas. The result is used for preliminary evaluation of the gasifier stability for fully closed and induced draft operation. Gasifier with better stability will be used for more comprehensive investigation of the effect of some principle parameters on the performance of selected gasifier for gasification of rice husk and sawdust feedstock.

2. Methods

2.1. Description of the gasifiers

Fig. 2 shows the design of downdraft gasifier I and downdraft gasifier II, respectively. Detail specification of the gasifiers are shown in Table 1. The gasifier I is made from Stainless Steel plate of 3 mm thickness. The plate is rolled and welded to cylindrical form. The gasifier has internal diameter of 300 mm and height of 950 mm. The gasifier is insulated with insulator cement of 25 mm thickness. The gasifier has five stages tuyer which 3 tuyers for each stage. The tuyer has a diameter of ¾ inch. Meanwhile, the gasifier II is made from Mild steel pipe which internal diameter of 300 mm and height of 725 mm. The gasifier is insulated with glass-wool of 50 mm thickness. Both gasifiers use perforated Steel grate with hole diameter of 20 mm.



(a) (b)

Fig. 2. Design of (a) gasifier I and (b) gasifier II (unit in mm)

Table 1. Specification of the gasifiers

Specification	Gasifier I	Gasifier II
Model	Throat-less downdraft	Throat-less downdraft
Internal dia.	300 mm	300 mm
Height	950 mm	725 mm
Tuyer	5 stages, ¾ inch diameter	5 stages, 1 inch diameter
Material	Stainless steel	Mild steel

2.2. Running the gasifiers

The gasifiers are tested on feedstock of rice husk and sawdust for different setup. Four setups are performed for the gasifier I (setup A, B, C, and D), and five setups are done for gasifier II (setup E, F, G, H, and I) as shown in Table 2. Fully closed top operation of gasifier I is performed for rice husk and sawdust gasification in setup A and D, respectively. Meanwhile, gasifier II is run in fully closed top mode for all setup.

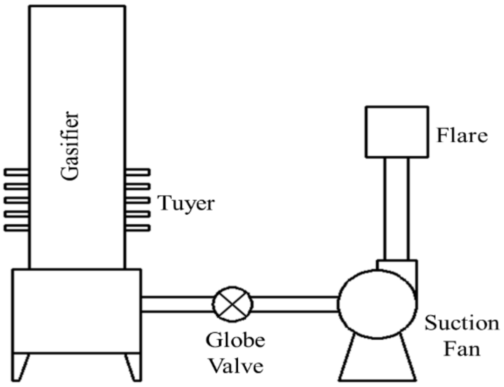
Table 2. Test setup

Gasifier	Setup	
Gasifier I	A	Rice husk gasification; closed top; primary air at 1st stage tuyer
	B	Rice husk gasification; primary air at 1st stage tuyer; secondary air at top hole of gasifier lid using blower
	C	Rice husk gasification; primary air at 1st stage tuyer; secondary air induced at top hole of gasifier lid
	D	Sawdust gasification; closed top; primary air at 1st stage tuyer
Gasifier II	E	Rice husk gasification; closed top; primary air at 5th stage tuyer; gasification initiation at 1st stage tuyer
	F	Rice husk gasification; closed top; primary air at 5th stage tuyer; gasification initiation at 2nd stage tuyer
	G	Rice husk gasification; closed top; primary air at 5th stage tuyer; gasification initiation at 3rd stage tuyer
	H	Sawdust gasification, closed top; primary air at 5th stage tuyer; gasification initiation at 1st stage tuyer
	I	Rice husk-sawdust blend gasification, closed top; primary air at 5th stage tuyer; gasification initiation at 1st stage tuyer

2.3. *Measurement of flammability duration of producer gas flame*

Fig. 3 displays schematic diagram of the downdraft gasifier system, feedstocks (rice husk and sawdust), and producer gas flame. The system consists of the downdraft gasifier, globe valve, induced draft fan, and flare. Procedure for running the gasifiers as follows: set the intended setup; load the feedstock into the gasifier; switch ON the suction fan and ignite the feedstock in the gasifier by means of torching through tuyer; and flaring producer gas in flare. After first flame in flare is obtained, do a record of flare condition (flaming or inflaming) every 5 minutes. Continuous flammability duration is obtained from continuous flaming condition of flare during gasification.

The procedure is performed for all setups and the achieved result of flammability duration are compared. In order to observe the self-regulating nature of induced air flow during gasification as reported by [35], measurement of air velocity during rice husk gasification in the gasifier II for the setup E, F, and G are also performed.



(a)

(b)

(c)

Fig. 3. (a) Schematic diagram of the gasifier system, (b) rice husk and sawdust, (c) flame of producer gas in flare

3. Results and Discussion

Fig. 4 shows continuous flammability duration of producer gas from rice husk gasification in gasifier I for different air supply setup. The continuous flammability duration of producer gas is achieved within 6 minutes for the use of only primary air and fully closed top condition. Aspirated air by induced draft fan (suction fan) through 1st tuyer is insufficient for stable gasification process. Gasification occurs in very slow rate and produces discontinuous producer gas. In order to increase the amount of air for gasification, additional secondary air is supplied, either with the use of blower or induced air through hole on the top of the gasifier. The use of the top blower increases continuous flammability duration of producer gas up to 16 minutes. This indicates that gasification is better than the use of only primary air. However, the use of the top blower causes gasification rate increases significantly which reduces batch operation time.

Meanwhile, maximum 32 minutes continuous flammability duration is achieved for the use of primary air at 1st stage tuyer and secondary air induced through top hole of gasifier lid. The maximum duration can be obtained with the use of additional secondary air. Unlikely with the use of top blower secondary air, no excessive air velocity occurs when top hole aspirated air is used. Hence, optimum continuous flammability duration of rice husk producer gas is achieved in the latest setup

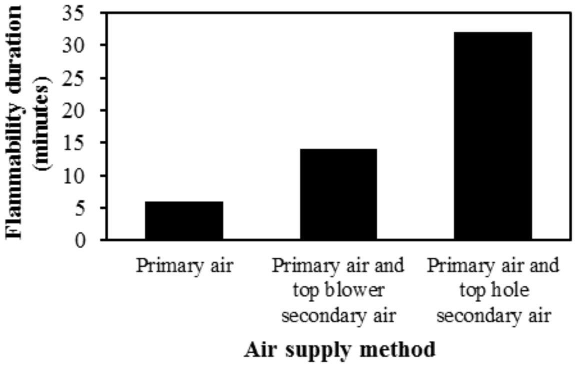


Fig. 4. Continuous flammability duration of producer gas from rice husk gasification in gasifier I.

The continuous flammability duration of producer gas from sawdust gasification is longer than from rice husk gasification for the use of only primary air and fully closed top operation as shown in Fig. 5. The continuous flammability duration of producer gas are 6 minutes from rice husk gasification and 8 minute from sawdust gasification. However, it is required more works during sawdust gasification. The channeling and bridging in reactor bed is found during sawdust gasification. The same phenomena were also reported by [23]. The problem causes blocking of ash flow downward to ash pit. To encounter the problem, sawdust bed in the reactor is pocked during sawdust gasification in this work.

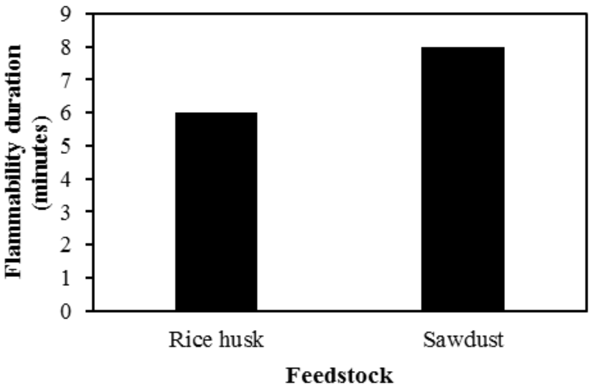


Fig. 5. Continuous flammability duration of producer gas from rice husk and sawdust gasification in fully closed top operation of gasifier I.

Fig. 6 indicates the continuous flammability duration of producer gas obtained from rice husk gasification in gasifier II. The runs are performed with primary air at 5th stage tuyer and gasification initiation at various stage tuyer (1st, 2nd, 3rd stage). The continuous flammability duration of producer gas are 21, 25, and 22 minutes for 1st, 2nd, 3rd stage tuyer initiation, respectively. The longest duration is achieved for initiation at 2nd stage tuyer. For 2nd stage tuyer initiation, air intake during gasification is the lowest within first half of stable flame duration as shown in Fig. 7. This outcomes on the continuous flammability duration. The graph also indicates that air velocity reduces during first half of stable producer gas flame and turns to increase for the next half. This is likely due to alteration in bed porosity of downdraft gasifier during gasification process as reported by [35]

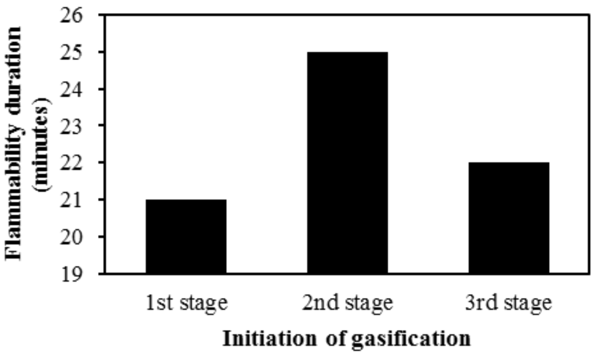


Fig. 6. Continuous flammability duration of producer gas from rice husk gasification in gasifier II

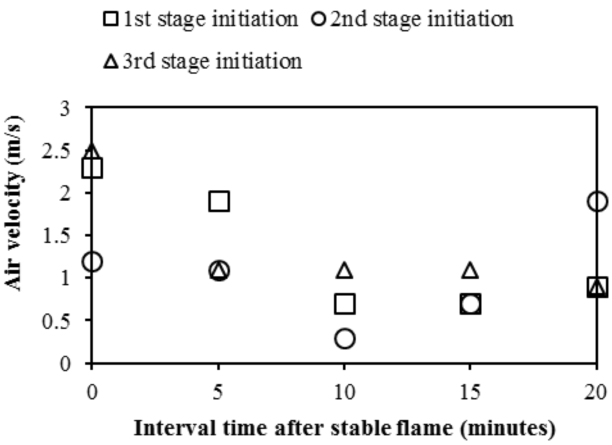


Fig. 7. Air inlet velocity at 5th stage tuyer during rice-husk gasification in gasifier II

Fig. 8 presents the comparison of continuous flammability duration of producer gas between gasifier I and gasifier II at fully closed top operation. The gasifier II is better than gasifier I for rice husk and sawdust gasification in terms of continuous flammability duration of producer gas. The continuous flammability duration of producer gas from rice husk gasification are 6 minutes and 30 minutes in gasifier I and gasifier II, respectively. Meanwhile, continuous flammability duration of producer gas from sawdust gasification are 8 minutes and 16 minutes in gasifier I and gasifier II, respectively. For fully closed top mode, gasification of rice husk and sawdust is more stable in gasifier II. It is because sufficient air entering gasifier by means of induced draft fan. The sufficient amount of air in gasifier II is likely due to shorter the height of the gasifier II than gasifier I (725 mm : 950 mm) and also may due to larger tuyer diameter of gasifier II than gasifier I (1 inch : 3/4 inch). In addition, the gasifier II also produces good continuous flammability duration of producer gas from gasification of rice husk-sawdust blend (1:1 by vol.), even the duration is the longest. The result indicates that the difficulty of sawdust gasification can be overcome by utilization of sawdust as additional feedstock to rice husk.

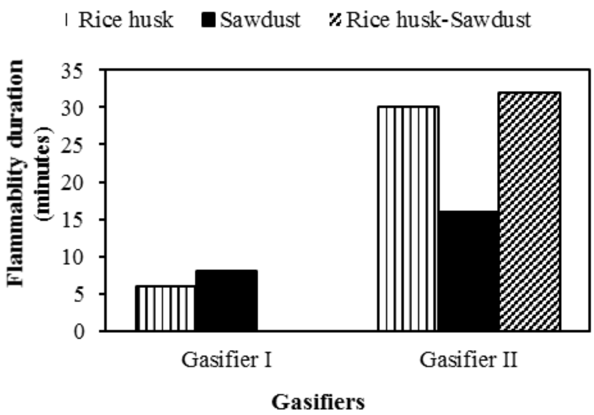


Fig. 8. Continuous flammability duration of producer gas from gasification of rice husk, sawdust and rice husk-sawdust blend in fully closed top operation of gasifier I and gasifier II

Fig. 9 displays the picture of typical uncontrolled producer gas flame in the flare which is observed in this work. According to vertical buoyant jet theory given in [31], the flame may divided into three different zone (jet dominated zone, jet-plume zone, and plume dominated zone). In the jet dominated zone, flame core is observed due to high producer gas velocity at this zone. Producer gas velocity decreases as increasing height, thus flame start to spread as seen in the jet-plume zone. The flame stretches more in the plume dominated zone. In order to obtain more detailed flame characteristic, experimental work with the use of control system is required which enable to control combustion parameters, such as air to fuel ratio.

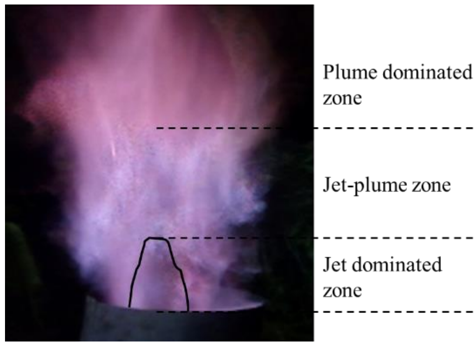


Fig. 9. Different zone of producer gas flame

4. Conclusions

Two model throat-less downdraft gasifiers are tested on feedstock of rice husk and sawdust for different setup. The two gasifiers are compared in terms of continuous flammability duration of producer gas. For the gasifier I, the maximum flammability duration is obtained from setup C

(Rice husk gasification; primary air at 1st stage tuyer; secondary air induced at top hole of gasifier lid). Meanwhile for the gasifier II, the maximum flammability duration is achieved from setup I (Rice husk-sawdust blend gasification, primary air at 5th stage tuyer; gasification initiation at 1st stage tuyer). For fully closed top setup, the gasifier II is more stable than the gasifier I in terms of continuous flammability duration of producer gas, either for rice husk or sawdust gasification. It is recommended that the gasifier II is suitable for more comprehensive study of rice husk and sawdust gasification.

Acknowledgements

The first author is grateful to Ministry of Research, Technology, and Higher Education (Kemenristekdikti) - Republic of Indonesia for providing scholarship to pursue Doctoral study at Department of Mechanical and Industrial Engineering, Faculty of Engineering, Universitas Gadjah Mada.

References

[1] J. J. Hernández, G. Aranda-Almansa, and A. Bula, “Gasification of biomass wastes in an entrained flow gasifier: Effect of the particle size and the residence time,” *Fuel Process. Technol.*, vol. 91, no. 6, pp. 681–692, 2010.

[2] S. Mohapatra and K. Gadgil, “Biomass: The Ultimate Source of Bio Energy,” *Int. J. Renew. Energy Res.*, vol. 3, no. 1, pp. 2–5, 2013.

[3] T. . Reed and a. Das, “Handbook of Biomass Downdraft Gasifier Engine Systems,” no. March, p. 148, 1988.

[4] C. Gai and Y. Dong, “Experimental study on non-woody biomass gasification in a downdraft gasifier,” *Int. J. Hydrogen Energy*, vol. 37, no. 6, pp. 4935–4944, 2012.

[5] P. N. Sheth and B. V. Babu, “Experimental studies on producer gas generation from wood waste in a downdraft biomass gasifier,” *Bioresour. Technol.*, vol. 100, no. 12, pp. 3127–3133, 2009.

[6] P. Basu, *Biomass Gasification and Pyrolysis*. .

[7] M. Puig-arnavat, J. C. Bruno, and A. Coronas, “Review and analysis of biomass gasification models,” *Renew. Sustain. Energy Rev.*, vol. 14, no. 9, pp. 2841–2851, 2010.

[8] Z. A. Zainal, R. Ali, C. H. Lean, and K. N. Seetharamu, “Prediction of performance of a downdraft gasifier using equilibrium modeling for different biomass materials,” *Energy Convers. Manag.*, vol. 42, no. 12, pp. 1499–1515, 2001.

[9] Wahyudi, T. Mesin, F. Teknik, Univ. Muhammadiyah, “Penelitian Nilai Kalor Biomassa :,” vol. 9, no. 2, pp. 208–220, 2006.

[10] A. Kaupp and J. R. Goss, “State of the art report for small scale (to 50 kW) gas producer - engine systems,” no. 53, p. 286, 1981.

[11] Z. Alimuddin, B. Zainal, P. Lahijani, M. Mohammadi, and A. Rahman, “Gasification of lignocellulosic biomass in fluidized beds for renewable energy development : A review,” *Renew. Sustain. Energy Rev.*, vol. 14, no. 9, pp. 2852–2862, 2010.

[12] E. Biagini, F. Barontini, and L. Tognotti, “Gasification of agricultural residues in a demonstrative plant: Corn cobs,” *Bioresour. Technol.*, vol. 173, pp. 110–116, 2015.

[13] V. R. Patel, D. S. Upadhyay, and R. N. Patel, “Gasification of lignite in a fixed bed reactor: Influence of particle size on performance of downdraft gasifier,” *Energy*, vol. 78, no. 0, pp. 323–332, 2014.

[14] A. T. Belonio and W. Preface, “Rice husk gas stove handbook,” 2005.

[15] O. Nakagoe, Y. Furukawa, and S. Tanabe, “Hydrogen production from steam reforming of woody biomass with cobalt catalyst,” *2012 Int. Conf. Renew. Energy Res. Appl. ICRERA 2012*, pp. 1-4, 2012.

[16] M. Aziz, T. Oda, and T. Kashiwagi, “Novel power generation from microalgae: Application of different gasification technologies,” *2015 Int. Conf. Renew. Energy Res. Appl. ICRERA 2015*, pp. 745–749, 2015.

[17] M. Aziz, T. Oda, T. Mitani, A. Uetsuji, and T. Kashiwagi, “Combined hydrogen production and power generation from microalgae,” *2015 Int. Conf. Renew. Energy Res. Appl. ICRERA 2015*, pp. 923–927, 2015.

[18] I. Romero, “The integration of a MSW plasma gasification plant in a Smart Grid in Andújar (Jaén),” *Int. Conf. Renew. Energy Res. Appl.*, no. October, pp. 20–23, 2013.

[19] M. Oku, T. Sakoda, N. Hayashi, and D. Tashima, “Basic characteristics of a heat and electricity combined generation system using biomass fuel,” *3rd Int. Conf. Renew. Energy Res. Appl. ICRERA 2014*, pp. 222–228, 2014.

[20] S. J. Yoon, Y.-I. Son, Y.-K. Kim, and J.-G. Lee, “Gasification and power generation characteristics of rice husk and rice husk pellet using a downdraft fixed-bed gasifier,” *Renew. Energy*, vol. 42, pp. 163–167, 2012.

[21] K. S. Lin, H. P. Wang, C.-J. Lin, and C.-I. Juch, “A process development for gasification of rice husk,” *Fuel Process. Technol.*, vol. 55, no. 3, pp. 185–192, 1998.

[22] J. Ye, C. Zhao, and Q. Zhang, “Zhongqing Ma,” vol. 10, no. 2, pp. 2888–2902, 2015.

[23] P. R. Wander, C. R. Altafini, and R. M. Barreto, “Assessment of a small sawdust gasification unit,” *Biomass and Bioenergy*, vol. 27, pp. 467–476, 2004.

[24] M. Simone, F. Barontini, C. Nicolella, and L. Tognotti, “Gasification of pelletized biomass in a pilot scale downdraft gasifier,” *Bioresour. Technol.*, vol. 116, pp. 403–412, 2012.

[25] A. Lickrastina, I. Barmina, V. Suzdalenko, and M. Zake, “Gasification of pelletized renewable fuel for clean energy production,” *Fuel*, vol. 90, no. 11, pp. 3352–3358, 2011.

[26] D. Pareek, A. Joshi, S. Narnaware, and V. K. Verma, “Operational Experience of Agro-residue Briquettes

Based Power Generation System of 100 kW Capacity," *Int. J. Renew. Energy Res.*, vol. 2, no. 3, pp. 477–485, 2012.

[27] H. Olgun, S. Ozdogan, and G. Yinesor, "Results with a bench scale downdraft biomass gasifier for agricultural and forestry residues," *Biomass and Bioenergy*, vol. 35, no. 1, pp. 572–580, 2011.

[28] A. L. Galindo, E. S. Lora, R. V. Andrade, S. Y. Giraldo, R. L. Jaén, and V. M. Cobas, "Biomass gasification in a downdraft gasifier with a two-stage air supply: Effect of operating conditions on gas quality," *Biomass and Bioenergy*, vol. 61, pp. 236–244, 2014.

[29] F. Guo, Y. Dong, L. Dong, and C. Guo, "Effect of design and operating parameters on the gasification process of biomass in a downdraft fixed bed: An experimental study," *Int. J. Hydrogen Energy*, vol. 39, no. 11, pp. 5625–5633, 2014.

[30] S. C. Bhattacharya, S. Shwe Hla, and H. L. Pham, "A study on a multi-stage hybrid gasifier-engine system," *Biomass and Bioenergy*, vol. 21, no. 6, pp. 445–460, 2001.

[31] K. B. Sutar, R. M.R., and S. Kohli, "Design of a partially aerated naturally aspirated burner for producer gas," *Energy*, vol. 116, pp. 773–785, 2016.

[32] P. Punnarapong, T. Sucharitakul, and N. Tippayawong, "Performance evaluation of premixed burner fueled with biomass derived producer gas," *Case Stud. Therm. Eng.*, vol. 9, no. October 2016, pp. 40–46, 2017.

[33] P. R. Bhoi and S. A. Channiwala, "Optimization of producer gas fired premixed burner," *Renew. Energy*, vol. 33, no. 6, pp. 1209–1219, 2008.

[34] H. A. Ozgoli, "Simulation of Integrated Biomass Gasification-Gas Turbine-Air Bottoming Cycle as an Energy Efficient System," *Int. J. Renew. Energy Res.*, vol. 7, no. 1, 2016.

[35] E. Balu and J. N. Chung, "System characteristics and performance evaluation of a trailer-scale downdraft gasifier with different feedstock," *Bioresour. Technol.*, vol. 108, pp. 264–273, 2012.