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Research Article

Experimental study of combustion of low-calorific producer gas from small scale biomass gasification within porous burner

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ABSTRACT

The aim of this experimental study is to investigate the combustion low-calorific producer gas within porous burner. The small scale downdraft biomass gasification for rural area was performed to produce gaseous fuel. Three types of wood in Thailand were used as raw materials to produce producer gas, i.e. Acacia-mangium, White popinac and Eucalyptus. The low heating values of producer gas were in the range of 3800–4232 kJ.kg^{-1} that are difficult to burn in conventional burner. Tapered and bilayer porous burners were used to overcome this limitation. The effects of air preheating modes, equivalence ratio and firing rate on thermal structure and pollutant emission were revealed. The results showed that the complete combustion with low emission of low-calorific producer gas was accomplished with low firing rate in the range of 2.8 – 3 kW. Both CO and NO_x emission were less than 160 ppm for all of tests. The combustion within tapered porous burner emitted small CO emission nearly zero for all of equivalence ratios. The tar reduction was 99.5% by combustion within porous burner.

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INTRODUCTION

Today the majority of energy consumption of the world is fossil fuels are used worldwide for electricity production, transportation and industrial. However, fossil fuels have limited reserves and deplete with utilization. Furthermore, emissions of greenhouse gases from fossil fuel systems are major environmental concern. This illustrates the importance of introducing and accelerating technological developments for studying strategy and design of electricity and energy system [1–13]. Biomass offers an interesting opportunity to substitute for fossil fuels.

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Biomass is organic material that derived from burning animal and plant waste (e.g. wood, agricultural waste and garbage). The raw materials used to produce biomass are infinite. Therefore, biomass is world-wide energy resource. Although, combustion either biomass or fossil fuels releases carbon dioxide, biomass absorb a nearly equivalent amount of carbon dioxide in photosynthesis process during growth. Biomass is a carbon-neutral energy source and using biomass as fuel can be reduced fossil dependency. The traditional utilization of biomass is directly burning in furnaces which are often characterized by low efficiencies and high release of toxic organic compounds. Many researchers have attempted to use biomass as fuel to replace petroleum oil for internal combustion engine. A comprehensive review of biomass utilization in internal combustion engine was reported by Sadeghinezhad et al. [14]. The different biomass materials provide different combustion characteristics [15]. Inadequate control of biomass combustion lead to a variety of air pollutants to the atmosphere [16]. Highlight technology delivers solution to appropriately use energy from biomass is gasification.

Gasification is an attractive alternative technology to achieve high quality syngas. This technology is a thermal conversion process that converts biomass into synthetic gas [17]. Unlike biomass materials, gaseous fuels can be distributed by pipeline from the plant to elsewhere. Moreover, synthetic gas provides cleaner combustion and easier to control than direct burning of biomass. Syngas production from biomass gasification can be divided into two main type: fixed bed and fluidized bed. The subtypes for the fixed bed type gasifiers are updraft and downdraft. The subtypes for the fluidized bed gasifiers are bubbling fluidized bed and circulating fluidized bed [18]. In the downdraft gasifier, the tar content of the producer gas is low because the produced gas is exited close to the reaction zone. Tar formation during devolatilization is thermally cracked in reaction zone before flow out at the exit. It is suitable for small application. However, the producer gas is diluted with nitrogen content. The heating value of synthetic gas is low. As a result, the stable combustion of low-calorific gaseous fuel in conventional burner can be difficult to accomplish.

Weinberg [19] revealed the concept of borrowing heat from a premixed flame to preheat the fresh mixture. A net energy transfer from the burned gases to the unburned gases is the effect of this recuperation. By this concept, at the same quality of mixture, the flame temperature of preheated mixture is greater than the adiabatic flame temperature. Moreover, Hardesty and Weinberg [20] indicated that this process extended the flammability limits over those for a conventional flame. Porous burner is a possible solution to achieve the limiting reactant quality of combustion by internal heat recirculation through porous structure. Within porous burner, the heat recirculation from the exhaust gases to the unburned gases through radiation and conduction through the porous structure. A variety of porous burner designs have been proposed by many researchers. The studies concluded that internal heat recirculation within porous burner results in extended the flammability limits [21–27]. They are useful comprehensive review papers in this area [28–30]. The review article deal with ultra-lean burn of methane within porous burner, with a highlight in practical aspects of burner design and operation and the application of the technology to real-world problems was proposed by Wood and Harris [31]. Moreover, the comprehensive survey about liquid fuel combustion in porous media and mathematical modeling of porous burner were reported by Abdul Mujeebu et al. [32–33]. Not only lean burn application but also rich burn application can be achieved by porous combustion. Rich combustion inside an inert porous burner were performed to evaluate hydrogen and syngas production and were revealed by many researchers e.g. Fay M et al. [34], Gao et al. [35], Pastore and Mastorakos [36], Smith et al. [37], Torres et al. [38], Ripoll [39] and Gonzalez et al. [40–41].

Porous media were used not only as burners but also heat transfer enhancement [42–45]. Furthermore, porous burners have been used to burn low grade fuel that have low-calorific value. Early studies focused on combustion of low-calorific simulated gaseous fuel in porous burner e.g. Al-Hamamre et al. [46], Francisco et al. [47–48], Keramiotis and Founti [49], Keramiotis et al. [50], and Huang et al. [51]. In addition, the numerical study of combustion of low-calorific producer gas within late mixing porous burner was proposed by Jirakulsomchok and Theinnoi [52]. However, in practical, producer gas from gasification process is possible fluctuation in quality and composition, have an effect on combustion stability. Experimental study of combustion of producer gas within porous burner was a few. Al-attab et al. [53] studied incorporated a downdraft gasification system with the two-layers porous burner for hot air production. The height of second porous layer serves as combustion zone were varied. The results indicated that the porous media burner provide an efficient combustion for the low heating value biomass producer gas with wide equivalence ratio range 0.33–0.71. The hot air production of 7 kWth can be utilized for drying process in small industries.

The present experimental study investigates combustion of low calorific producer gas from small biomass gasification within a porous burner. Cooperation between small-scale downdraft gasifier and porous burner were performed. The porous burner was used to burn the real producer gas that is fluctuation in quality and composition. The combustion of low firing rate producer gas that difficult to operate in conventional combustion system and the result of tar elimination by porous burner were studied to broaden knowledge of Al-attab et al. [54]. The optimum wood types for the downdraft gasifier was determined. Two configuration of porous burner, tapered porous burner and bilayer porous burner were used in this study. The effect of preheating and non-preheating air is investigated. As well as the effect of equivalence ration and firing rate is concluded.

EXPERIMENTAL APPARATUS

Figure 1 shows a schematic of the experimental setup. The experimental apparatus consists of fixed bed downdraft gasification, porous combustor system. The gasifier is made of stainless steel 304 pipe with a diameter of 31.5 cm and a height of 100 cm. The small-scale downdraft gasifier was developed to use for rural area in Thailand [55]. The throat size is 6 cm. Four K-type thermocouples, $T_1 - T_4$ are installed and locations are shown in Fig. 2. The producer gas from gasifier is cleaned in tar treatment set before flow into porous burner. Evergreen fast-growing tropical trees, i.e. Acacia-mangium, White popinac and Eucalyptus were used as materials to produce producer gas. Raw locks were cut to optimum size of wood chip for the gasifier and dried. At the first stage, the air was supplied to gasifier that contains wood chip. The pilot flame was utilized to startup process. In tar treatment set, Isopropanol (IPA) in wet scrubber was act as solvent to trap tar. Producer gas compositions was analyzed by Shimadzu Gas Chromatography Model 2014 is equipped with the advanced flow controller (AFC) technology. The AFC is standard for both capillary columns and packed columns. Accurate flow rate control via AFC has higher-level repeatability of retention time and peak area, enabling a higher level of analyses.

Figure 3 shows the porous combustor system. The combustion chamber is surrounded by an air jacket for air preheating. Two configuration of porous burner was considered in this study: tapered porous burner and bilayer porous burner are showed in Fig. 3a and Fig. 3b respectively. The tapered porous burner is tapering vessel is filled with aluminum oxide balls with diameter of 25 mm. The tapered pipe is 110 mm in height. While the bilayer porous burner is a cylinder stainless pipe (80 mm in inside-diameter and 400 mm in height) is filled with two type of material. The first layer of bilayer porous burner is a 25 mm packed of metallic wire screens with mesh size of 100 mesh/in. The first layer of bilayer porous burner was designed to prevent flame flashback. The second layer consists of a packed bed of Al_2O_3 with a diameter of 10 mm for combustion zone. Testo 350-Portable emission analyzer is utilized to measure emission form combustion process. Tar collection set is

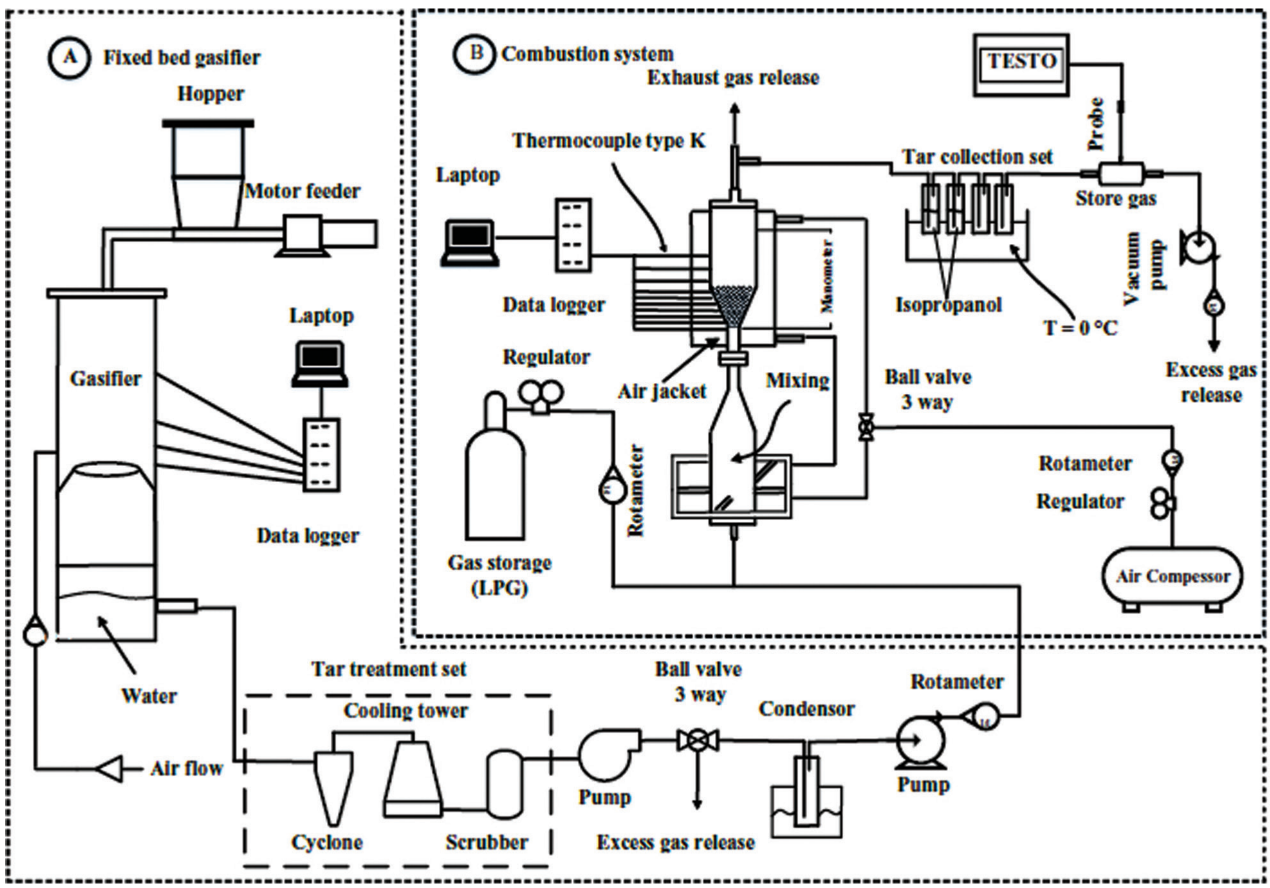


Figure 1. Schematic of the experimental setup.

installed to analyst tar after burning at exhaust gas release. At the beginning, the porous burner was preheated by combustion of liquefied petroleum gas (LPG) at near stoichiometric condition. A pilot flame was inserted through the small ignition port. When the combustion within packed bed occurred, the pilot flame was removed and the ignition port is closed. Then, the producer gas from gasifier was supplied into porous burner while the flow of LPG was reduced. Until the main flame of pure producer gas and air was stabilized, then adjust the operating condition. The combustion air was pressurized by air compressor and adjusted by rotameter regulator. The air preheating and nonrepeating mode were switched by three-way ball valve. Ten K-type thermocouples, $T_1 - T_{10}$ are placed to investigate thermal structure. Data-logger are used to continuously record temperature profiles both in gasifier and porous burner.

Emission of the dry combustion products at the porous burner is monitored by using a portable emission analyzer designed especially for quasi-continuous measurement. A gas processing system of NO_x and CO is especially tuned for electrochemical sensors, ensuring long-time stability and accuracy of measurement. The measuring range of the analyzer is 0–4,000 ppm for the NO_x and 0–10,000 ppm for the CO with a measuring accuracy of about ±5 ppm and resolution of 1 ppm for both NO_x and CO. In the experiment, all measured emission data are corrected to 0% excess oxygen and dry-basis. Fuel flow rate, air flow rate, and pressure difference are also recorded using conventional measuring devices. Repeated measurement shows an uncertainty of about 10% for temperature and species concentration.

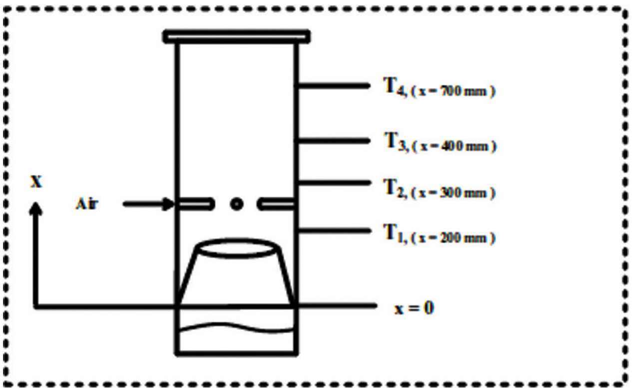


Figure 2. Schematic of gasifier.

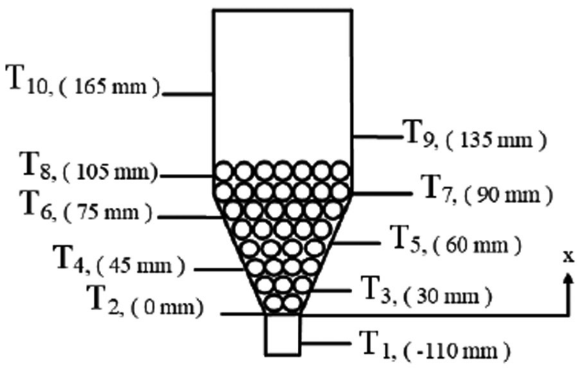
RESULTS AND DISCUSSION

Biomass Type

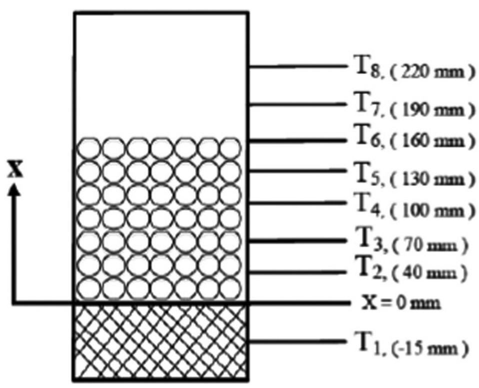
The effects of three biomass types (Acacia-mangium, White popinac and Eucalyptus) on gas composition obtained through gasification are presented. Preliminary experiment was performed to find optimum condition for producer gas production in the down-draft gasifier. The solid equivalence ratio (ER) was varied in the range of 0.5 to 0.7. The optimum ER for producer gas production and low heating value of three types of wood are presented in table 1. The low heating values were in the range of 3800–4232 $kJ.kg^{-1}$ that are difficult to burn in conventional burner. Figure 4 shows effect of three types of biomass on gas composition of producer gas. Acacia-mangium wood provides highest low heating value at ER of 0.53 because it obtains high combustible gas composition that is presented in table1. Therefore, in this study, the Acacia-mangium wood is considered as raw material to produce gaseous fuel for porous burner.

The Effect of Porous Burner Geometry

Figure 5 illustrates the effect of porous burner geometry on temperature profiles at firing rate (FR) of 3 kW. The equivalence ratio (Φ) was varied from 0.8 to 0.9 in this experiments. Increasing Φ at a fix firing rate done by decreasing combustion air flow rate while producer gas flow rate was fixed. An increase in the Φ of lean mixture, the quality of mixture is increased causes an increase in



a. Tapered porous burner



b. Bilayer porous burner

Figure 3. Schematic of porous burner.

the flame temperature for both porous burners geometry. The increase in Φ does not significantly affect flame location. The results indicated that complete combustion can be occurred with in both tapered and bilayer porous burner. The small emission release is shown in figure 6. Both CO and NO_x emission was less than 160 ppm for all of tests. Especially for tapered porous burner, the CO emission was nearly zero for all of Φ. The porous burner with tapered shape is found to be more efficient than the bilayer porous burner. The narrow diameter at the upstream zone results in high flow velocity of fresh mixture and high convective heat transfer at the pre-flame zone. This is lead to the short length for complete combustion and more compact combustors design. Moreover, the first layer of bilayer porous burner is designed to be tiny pore for preventing flame flashback that cause a clogging risk from impurity of tar.

The Effect of Firing Rate

Figure 7 illustrates the effect of firing rate (FR) on temperature distribution in the tapered porous burner at Φ = 0.95. Increasing firing rate at a fixed Φ was carried out by increasing both gaseous fuel and air flow rate. The increase in FR cause an elevation in flow velocity and convective heat transfer driving flame upstream. The effect of FR on CO and NO_x emission is shown in Fig. 8. The small NO_x are not over 120 for all of FR while the CO emission is not over 50 ppm. The CO emission is nearly zero from FR = 2.8 to 3. However, the small range of FR was varied. The upscale of biomass gasification for producer gas productivity should be done in the future study.

Table 1. Influence of wood type on low heating value

Type of wood	Optimum ER	LHV ($kJ.kg^{-1}$)
Acacia-mangium	0.53	4232
White popinac	0.64	4000
Eucalyptus	0.65	3800

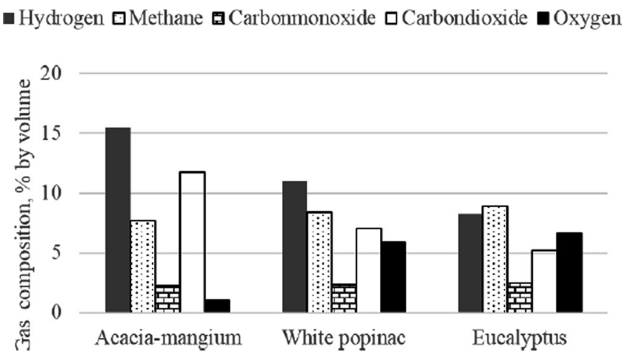


Figure 4. Effect of biomass on gas composition of synthetic gas.

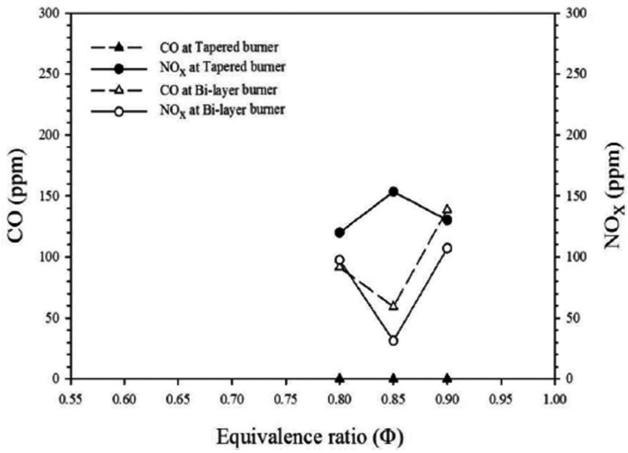


Figure 6. CO and NO_x emission of tapered and bilayer porous burner at FR = 3 kW.

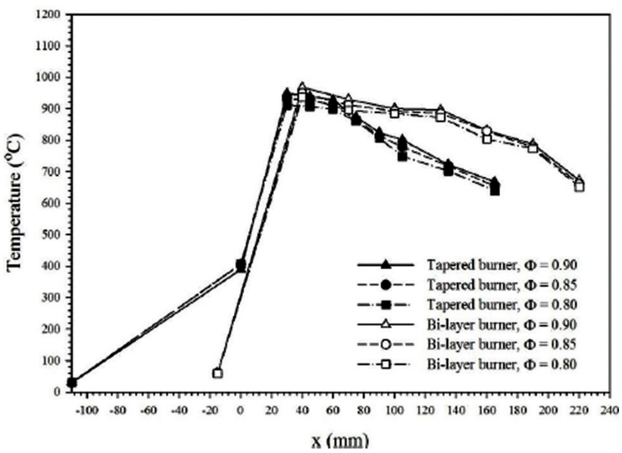


Figure 5. Temperature profiles of tapered and bi-layer porous burner at FR = 3 kW.

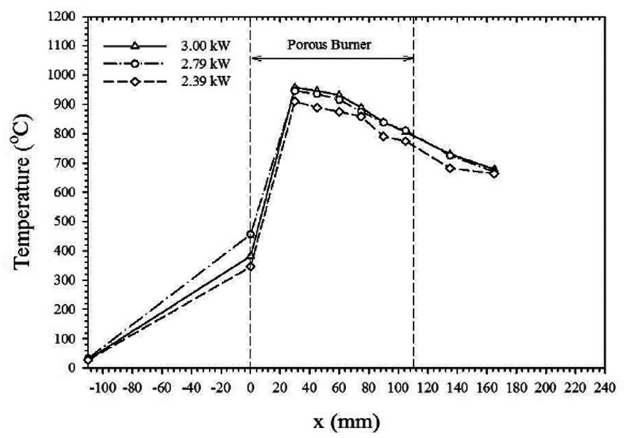


Figure 7. Effect of firing rate on temperature profile at Φ = 0.95.

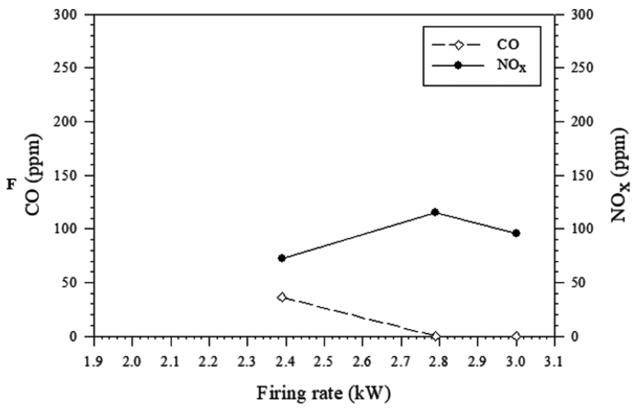


Figure 8. Effect of firing rate on CO and NO_x emission at $\Phi = 0.95$.

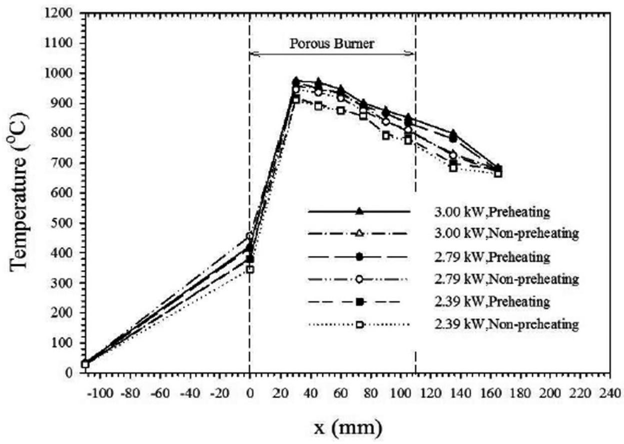


Figure 9. Effect of air preheating on temperature profile at $\Phi = 0.95$.

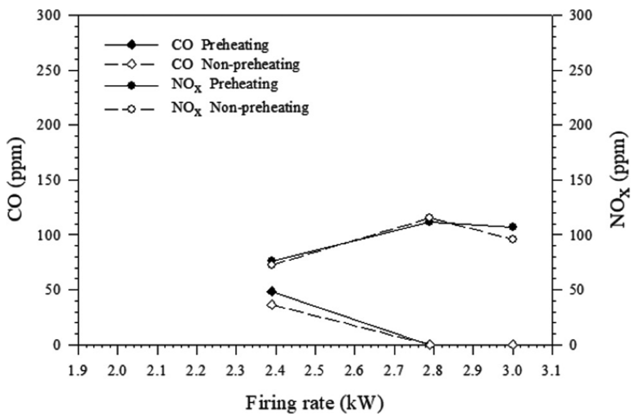


Figure 10. Effect of air preheating on CO and NO_x emission $\Phi = 0.95$.

The Effect of Air Preheating

Fig. 9 shows the effect of air preheating on temperature distribution of tapered porous burner. The air preheating and non-preheating modes were adjusted by using 3 ways ball valve that illustrated in fig. 1. The FR was varied from 2.39 to 3.0 kW at a fix equivalence ration of 0.95. The results indicated that the air preheating dose not significantly effect on flame temperature and thermal structure of the system. This may be the small FR range in the test contributed the small air flow velocity. The convective heat transfer in the air jacket was not strongly enough to preheat air. However, the CO and NO_x emission (Fig. 10) are remained small both preheating air and non-preheating air cases.

Tar Reduction by Porous Burner

The tar sampling system setup and tar sampling method proposed by Hasler and Nussbaumer [55], was guideline to design and modify in this study. The tar sampling method is condensing the tar in a cooled liquid isopropanol solvent. The isopropanol was removed by a rotary evaporator. The residual weighed was tar. The value of tar was converted into grams of tar per Nm^3 of gaseous fuel. Period for sampling was found by sufficient amount of tar for gravimetric determination. The amount of tar collection in porous particles was determined by isopropanol absorption. The tar collection at surface of porous particles were soaked in liquid isopropanol by sufficient time to dissolute. The result indicated that the tar reduction was 99.5% by using tapered porous burner. This is due to tar quantity is reduced with high temperature combustion within porous burner.

CONCLUSION

The propose of this work is to investigates combustion of low calorific producer gas from small biomass gasification within a porous burner. Downdraft gasifier was used to produce gaseous fuel. Two configuration of porous burner, i.e. tapered and bilayer porous burner were considered to determine the optimum configuration of porous burner. The effect of air preheating modes, equivalence ratio, firing rate on temperature profiles and pollutant emission were reported. The main conclusions were as follows:

- The Acacia-mangium wood at ER of 0.53 was optimum condition to produce producer gas in the small downdraft gasifier in this study.
- The complete combustion with small emission can be occurred within two type of porous burner.
- The tapered porous burner was optimum configuration to burn producer gas.
- An increasing in equivalence ratio causes an increase in the flame temperature, while it does not significantly affect reaction zone.
- The increase in firing rate cause an elevation in flow velocity and convective heat transfer driving flame upstream.

- The tar reduction was 99.5% by using tapered porous burner.
- The optimum operating condition is at firing rate of 3 kW and Φ = 0.95 because under this operating condition provide maximum temperature with low emission both CO and NO_x.

DATA AVAILABILITY STATEMENT

No new data were created in this study. The published publication includes all graphics collected or developed during the study.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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