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Experiments and analysis of propagation front under biomass stratified downdraft gasification

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Abstract

The paper analyses the results of experiments on the stratified downdraft configuration in a gasification reactor. The experimental study using wood pallet as fuel. Air flow rate was varied from 40 lit/min to 90 lit/min. The influence of air flow rate on 1.) Layer height separation 2.) Flame smoldering propagation 3.) Fuel residual carbon composition 4.) Fuel consumption 5.) Equivalent ratio. The result shows that flame smoldering propagation is in counter direction of the supply air for all cases. The propagation speed is increased with the increasing air flow rate supplied from 40 lit/min to 60 lit/min. The peak propagation speed observed at 60 lit/min of supply air. The layer separation is divided into two distinct zone which comprised of 1.) Combustion zone and 2.) Reduction zone. Combustion zone is determine as heat release region. It is dominate by oxidation reaction. While reduction zone is depicted by reduction endothermic mechanism. It is revealed from the thermocouple that there is heat generation zone that cause temperature raise up along reactor. Heat and pyrolysis combustible gas was transport in counter direction to the supply air flow rate which was dominate by diffusion regime at the range of air supply of 40 lit/min to 60 lit/min. This resulting in more speed in counter direction of smoldering propagation in this range of air supply. While increasing air supply rate above 60 lit/min, the convection heat transport has become more effective. Heat and mass is transport in co-direction with supplied air in convection transport mode, which resulting in less diffusion transport in counter direction of supply air. This phenomena confirm by propagation speed is lower in the range of air supply from 60 to 90 lit/min. High carbon residual composition was observed for all range of the air flow rate. The calculated equivalent ratio was varied from 0.42 to 0.90.

Keywords: Flame front, Propagation rate, Biomass gasification

1. Introduction

Direct combustion and gasification are two methods to extract heat energy from biomass or solid fuels. Heat energy may use directly via heat exchanger in heating application or taken in heat add process in power generation application. Heat added process are either internal or external combustion regime. Direct combustion of biomass is unable to employ in internal combustion engine. It has to be combusted externally and transport heat to working fluid, usually the steam. In contrast to gasification, which gaseous fuel from reactor is generally route to heat engine and internally combusted for power generate. Gasification integrate with heat engine claimed to achieve more thermal efficiency comparing to direct combustion. Due to thermodynamics advantage of working fluid of air superior to bottom steam cycle.

Direct combustion method has less ability to control shift reaction [1,2]. Heat release is straight forward from two time phase comprised of 1.) Combustion of pyrolysis gas and 2.) Char reacting with oxygen. In Direct combustion, heat is generally transport to point of use via heat exchanger. Gasification is an overall sub-stoichiometric process, converts solid fuel to gaseous fuel. During this process, the fuel undergoes series of thermochemical processes of 1.) Pyrolysis combustion 2.) Devolatilization 3.) Hetorogeneous char combustion 4.) Char reduction 5.) Drying [3].

2. Stratified downdraft gasifier

The process consists of 1.) Drying 2.) Pyrolysis combustion 3.) Reduction. During flaming, volatiles are released and react with the air flowing through the pore space of the stacked bed of biomass. The reaction is executed as auto-ignition in the pore space where the air and volatile mixture ratio and temperature is within flammable limit. Drying zone is on the top above pyrolysis combustion layer where heat is transport from pyrolysis combustion layer in conduction and radiation mode. Flaming pyrolysis layer height is limited by available oxygen in supply air stream. The movement of whole flaming pyrolysis layer is move toward the flame front in counter direction of the supply air [3].The speed of the layer propagation is depends on the transport phenomena where heat, pyrolysis gas and oxygen are in flammable constituent. Biomass is transformed to black-char in next layer after releasing all volatiles from pyrolysis combustion zone. The black-char layer has reduction kinetic which the endothermic reaction taking place. Endothermic reaction layer was initiate with the incoming of rich steam and carbon dioxide (combustion product) while no oxygen present (no oxidation), and available char and adequate temperature for reduction kinetic to occur. Reduction kinetic is transform thermal energy of non-combustible gas into chemical energy of combustible gas which is mainly CO and H_2.

Gasification has more ability to manipulate on shift reaction before execute gas combustion. Therefore, gasification has generally higher thermal efficiency in heating application [4]. Moreover, gasification is considered to be cleaner and higher flame temperature comparing to direct combustion. The higher flame temperature is considered as advantage when integration with heat exchanger in heating application. In contrast to direct combustion, where heat release is directly from pyrolysis gas and char combustion without any shift reaction involved.

Gasification still has weak point especially in large scale application. For example, it has more sensitivity to environment condition. It was consider lower reliability in large scale compare to direct combustion [5]. Another gasification issue is heavy hydrocarbon tars that is condensed on cool surface area generate blocking issue in gas transport system.

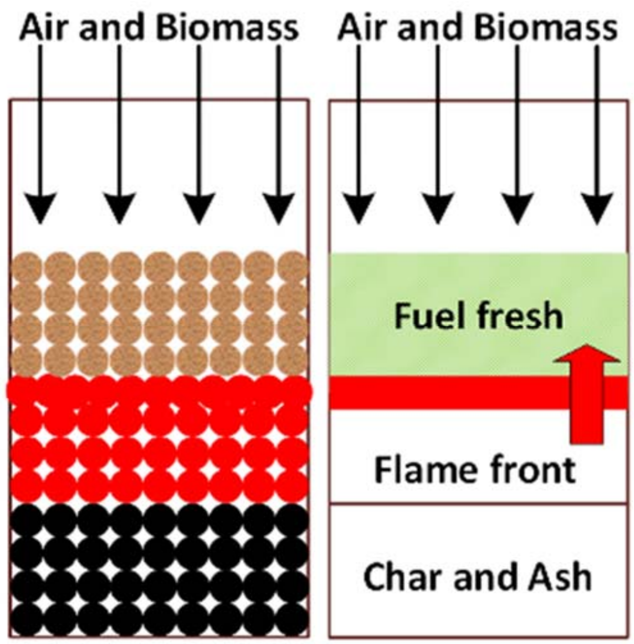

Fig. 1 Propagation transport in stratified downdraft gasifier

In this paper, study on temperature propagation of a stratified downdraft gasification has been conducted. The air supply was vary in the range of 40 lit/min to 90 lit/min. The thermocouple was installed along axial direction of the reactor. The temperature was recorded every 10 seconds for all thermocouple during gasification process. The smoldering propagation, layer height separation and transport phenomena analysis was performed in accordance to the temperature data. Qualitative justification on carbon residual base on visual analysis has been made.

3. Materials and method

The experiments are conducted in a packed bed gasifier as shown in Fig. 2a. The reactor is made up of steel and has 76 mm inner diameter and 500 mm height. This reactor is insulated with a ceramic fiber blanket throughout its length to reduce the heat losses from it. An air inlet as shown in Fig.2a.The thermocouple arrangement along the reactor length is also shown in Fig. 2b. The measured parameters during the experiments are biomass consumption rate and bed temperature at different locations along the length of the reactor. Nine of K type thermocouples are used to measure bed temperatures at various locations of the reactor.

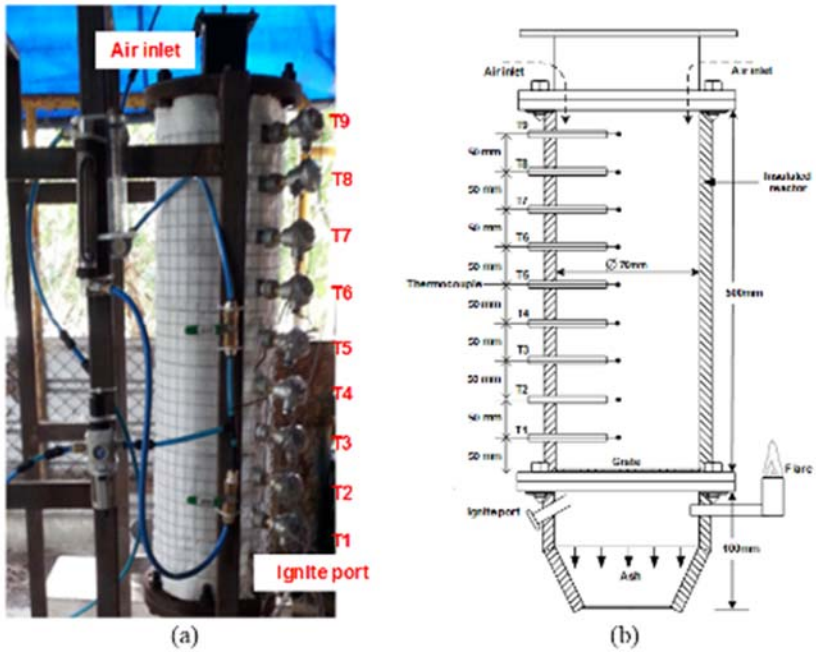

Fig. 2 (a) Air inlet and thermocouple arrangement in the reactor. (b) Thermocouple arrangement in the reactor.

The flame propagation rate is calculated by knowing the distance between two consecutive thermocouples and the time required to reach a particular temperature between those thermocouples. The distance between two consecutive thermocouples is 5 cm. The time required to reach the reference temperature between two consecutive thermocouples is calculated by using the temperature profile. The flame propagation rate is calculated by using the following relation Eq.(1) [5] and the equivalence ratio (Φ) for each run is calculated by Eq. (2) [5]

Biomass (Wood pallet) was used as fuel in all experiments. The results of ultimate and proximate analysis are listed in Table.2. It is shown that wood has a high volatile content while low fixed carbon content and heating value.

$$\text{Propagation rate(cm/min)} = \frac{\text{Distance between thermocouples(cm)}}{\text{Time required to reach the reference temperature(min)}} \quad (1)$$

$$\Phi = \frac{\text{(Flow rate of air/Rate of biomass consumption)}}{\text{(Flow rate of air/Rate of biomass consumption)}\big|_{Stoichiometic}} \quad (2)$$

Table. 1 Showed all equivalent ratio at air flow rate

Air flow rate(lit/min)	Equivalent ratio
40	0.45
50	0.75
60	0.90
70	0.58
80	0.42
90	0.43

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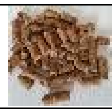
Table. 2 Fuel properties.

Sample	Moisture(%)		
Wood pellet 	5.81		
Ultimate analysis		Proximate analysis	
Parameter	(% d.b.)	Parameter	(% d.b.)
C	45.42	Fixed carbon	16.16
H	6.31	Volatile matter	81.41
O	45.54	Ash content	2.43
N	0.54	Calorific value (MJ/kg)	17.50

3. Result and discussion

Propagation rate was calculated by equation (1) .The propagation rate is slowest at air flow rate of 40 Lit/min. The propagation speed is increasing with increased supply air flow rate in the range of air supply 40 lit/min to 60 lit/min. The increasing air flow rate in this range resulting in higher kinetic rate at the combustion zone corresponding to the higher maximum temperature. There are two mode of heat and pyrolysis gas transport which are 1.) Diffusion mode in the counter direction with the supply air 2.) Convection mode in the co-direction with the supply air. Both heat and mass transfer mode is increasing with the increasing supply air of the range 40 lit/min to 60 lit/min. The diffusion mode is increase because of the higher gradient of temperature and pyrolysis gas species which resulting from higher kinetic rate at combustion zone. While the convection of heat and pyrolysis gas in downward direction is also increasing because of the increasing air flow rate. The increasing in diffusion transport mode promote the propagation speed of the smoldering in counter direction of the incoming air supply in this range of supply air.

The convection transport is becoming dominate in the range of air supply of 60 lit/min to 90 lit/min. The increasing in convection is resulting in lower peak temperature because of the convection heat loss. The kinetic rate is slower with the lower temperature. The property gradient is lower in this range of air supply. The decreasing in diffusion transport mode attenuate the propagation speed of the smoldering in counter direction of the incoming air supply in this range of supply air. The increasing in air flow rate in the range of 60 lit/min to 90 lit/min is resulting in slower speed of smoldering propagation.

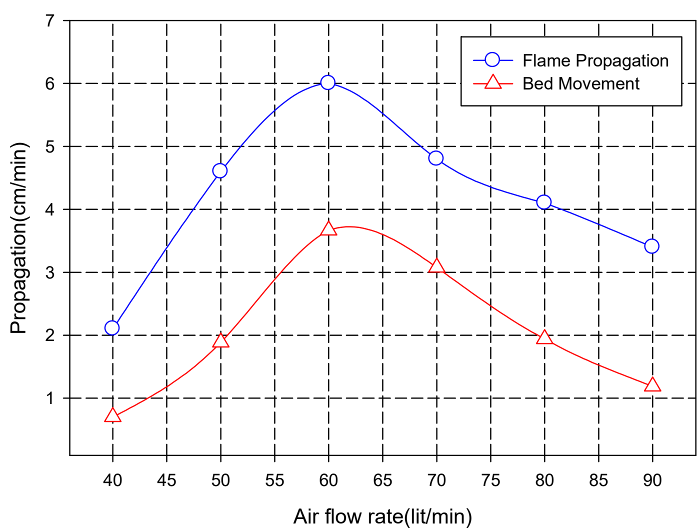


Fig. 3 Smoldering propagation speed with different air flow rate

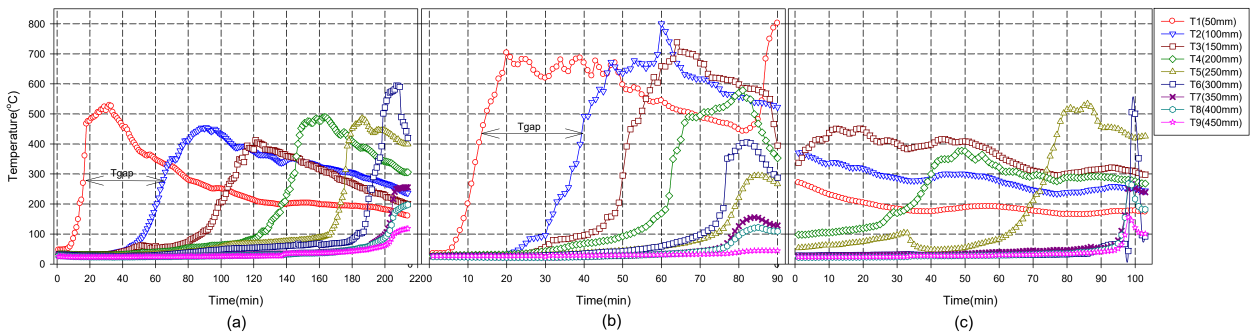


Fig. 4 Temperature profiles inside the reactor at air flow rate (a) 40 lit/min (b) 60 lit/min (c) 90 lit/min

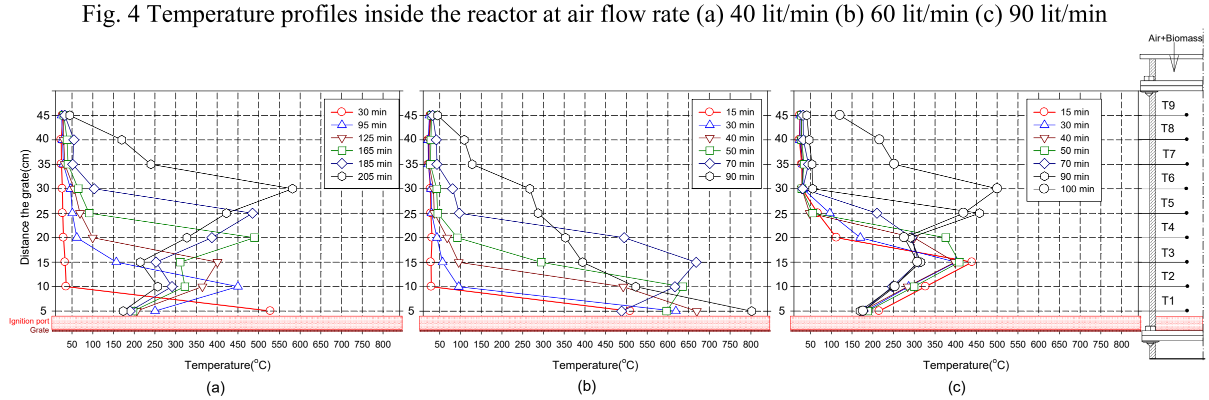


Fig. 5 Temperature distribution at different time in the reactor at air flow rate (a) 40 lit/min (b) 60 lit/min (c) 90 lit/min


40 lit/min


50 lit/min


60 lit/min


70 lit/min


80 lit/min


90 lit/min

Fig.6 Un-burn carbon for all air flow rate.

The temperature distribution along axial direction as shows in figure 4 and 5 in the reactor demonstrate heat release zone due to combustion. The temperature of fresh in coming air that supply from the top portion of the reactor is raise steeply at the combustion zone. Strong diffusion transport of heat in counter direction of the air supply is indicated by sharp temperature gradient in this zone. The temperature is gradually reduce after combustion zone due to reduction kinetic which endothermic reaction is taking place in this region.

After reduction zone the temperature is continue slightly reduce from heat loss of the hot gas to the fuel residual and the rector wall heat loss. The reduction kinetic is terminate due to cold quenching in this region as shows in figure 5. There was evident of unburned carbon residual for all cases. The propagation front is traveling with speed that were not allowing enough time for char to completely burn out as shows in figure 6.

6. Conclusion

The experimental result shows that the flame propagation in a stratified downdraft gasifier has two distinct characteristic which are 1.) Diffusion dominate range 2.) Convection dominate range. The diffusion transport resulting in faster speed of the flame propagation in the counter direction of the supply air in the range of 40 lit/min to 60 lit/min. While the convection heat loss in downstream direction of the supply air was dominated in the range of 60 lit/min to 90 lit/min. Convection heat loss in downstream direction is resulting in lower temperature in combustion zone. The property gradient is lower in this range of air supply. The decreasing in diffusion transport mode attenuate the propagation speed of the smoldering in counter direction of the incoming air supply in this range of supply air. Visual investigate on the fuel residual demonstrate considerable un-burn carbon for all of the cases.

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