Performance Evaluation of a Down Draft Double Chamber Pyrolysis Reactor under Field Conditions

A.M.Y.W. Alahakoon* A.K. Karunarathna[1] and R.S. Dharmakeerthi[2]

Postgraduate Institute of Agriculture
University of Peradeniya
Sri Lanka

ABSTRACT: *Sequestration of carbon through production of biochar has been recognized as a feasible approach to combat global warming. The application of biochar production technology in industrial scale is still new to developing countries due to high complexity and specificity of pyrolysis technology. Therefore, this study aimed to evaluate a small scale pyrolysis unit (Down Draft Double Chamber pyrolysis reactor – DDDC reactor) to be used in continuous biochar production with the use of paddy husk as the both feedstock and fuel material. The temperature variation, syngas composition and energy value, mass and energy balances of the DDDC reactor were evaluated through field trials. The average temperature varied from 330 °C to 560 °C from bottom to the top of the reactor fulfilling the temperature requirement for pyrolysis. However, fluctuations in temperature were observed during trials due to low energy supply through paddy husk as the fuel. This suggested a need of using a supplementary fuel source to operate the reactor. The biochar recovery of the reactor was 32% (dry matter basis) and the average biochar production rate was 1 kg/h for material input of 4.42 kg/h of paddy husk and 0.77 kg/h of coconut shell as fuel sources. The average raw syngas composition (v/v) was 20.78% CO, 13.3% CO_2, 3.87% CH_4, 0.3% C_nH_m, 6.91% H_2, 0.68% O_2, and 54.16% N_2 with an average energy content of 5.34 MJ/m^3. This study showed the potential for optimizing and upscaling a continuous mode paddy husk pyrolysis reactor for industrial applications.*

Keywords: *biochar, paddy husk, pyrolysis, pyrolysis reactor, syngas quality, temperature variation*

INTRODUCTION

Ever increasing energy demand and negative impacts of burning fossil fuels have driven the attention to explore new potentials for energy production. Thermochemical reactions of biomass and energy generation, such as pyrolysis, is one of the feasible methods discussed during the recent past (Panwar, 2009). Less complex operation process and low operation cost made the pyrolysis a widely applied tool as an energy alternative (Aziz *et al.*, 2018). There are many advances in the technologies related to pyrolysis. However, the availability of tailor-made technologies for developing countries are lacking (Woolf *et al.,* 2017). Especially, agricultural countries produce ample amount of agricultural wastes that can be used as alternative energy sources through biomass pyrolysis. However, there is a need to acquire safe, efficient pyrolysis technologies for an affordable cost.

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[1] Department of Agricultural Engineering, Faculty of Agriculture, University of Peradeniya, Sri Lanka.
[2] Department of Soil Science, Faculty of Agriculture, University of Peradeniya, Sri Lanka.
* Corresponding author: yushaniamyw@gmail.com

Despite energy generation, biochar production through pyrolysis has drawn considerable attention in the field of agriculture as a soil amendment and as an approach for atmospheric carbon sequestration (Woolf, *et al*., 2017). Therefore, the production of biochar with available agricultural wastes and application to the agricultural fields have identified as successful methods for resource recovery through pyrolysis (Sylva *et al*., 2014; Putun *et al*., 2004; Mullen, *et al*., 2010). Biochar production industry in Sri Lanka is being mostly operated in medium or small scale with agro-based biomass materials. Various studies have been conducted during recent years to develop and promote the biochar production in Sri Lanka. Biomass sources such as gliricidia woods, paddy husk, refused tea (Amarasinghe *et al.,* 2016), coconut shell, coconut husk, corn cobs, rubber wood and biomass fraction of municipal solid waste (Bandara *et al.,* 2016; Dharmakeerthi, 2014; Dharmakeerthi *et al.,* 2014) were used with these experiments. Most of these developed technologies are suitable with batch operations and there is a need to introduce continuous type pyrolysis technologies, which are more suitable for commercial applications. Auger type (Brown, 2009; Brassard, *et al*., 2017), fluidized bed (Boateng, *et al.,* 2007; Kersten, *et al*., 2005), rotating cone reactors (Westerhout, *et al.,* 1998; Wagenaar, *et al*., 1995) are some of the popular technologies that are developed previously. It is also possible to use the down draft technology to support continuous pyrolysis. In the down draft technology, feedstock materials are transferred through a vertical reactor from top-to-bottom while supplying heat and pyrolysed products are taken out from the bottom of the reactor. This study was conducted to design and fabricate a continuous type Down Draft Double Chamber (DDDC) pyrolyser reactor and evaluate the performance of that reactor for biochar production using paddy husk as both the feedstock and energy source.

METHODOLOGY

System Design

A continuous type small scale DDDC reactor was designed and fabricated to evaluate the performance of the down draft, double chamber technology to pyrolyse paddy husk. General specifications of the reactor are summarized in the Table 1.

Table 1. General specifications of the Down Draft Double Chamber reactor

Specification	Description
Reactor type	Continuous type
Portability	Stationary
Feedstock	Paddy husk
Fuel type	Paddy husk and coconut shell (supplementary)
Heat transfer rate	Slow
Method of heating	Indirect heating
Loading and unloading of material	Manual

Schematic diagrams of the designed DDDC reactor is shown in the figure 1 and figure 2.This DDDC reactor mainly consists of two chambers where inner small chamber (diameter=30 cm and height=88 cm) used as the pyrolysis chamber and outer larger chamber (diameter=50 cm and height=106 cm) used for fuel combustion. Fuel (paddy husk) is supplied through a feeder with an air flow and the combusted hot air flows through the exhaust gas outlet. Paddy husk for the pyrolysis is fed through the feedstock inlet and the produced biochar is taken out from the biochar outlet through an auger conveyor. Combusted fuel ash is taken out from the ash outlet and the produced syngas is transferred to a syngas purifying system via syngas outlet. Syngas was purified by passing through a bubbling scrubber system where a $Ca(OH)_2$ solution was used as the scrubbing media.
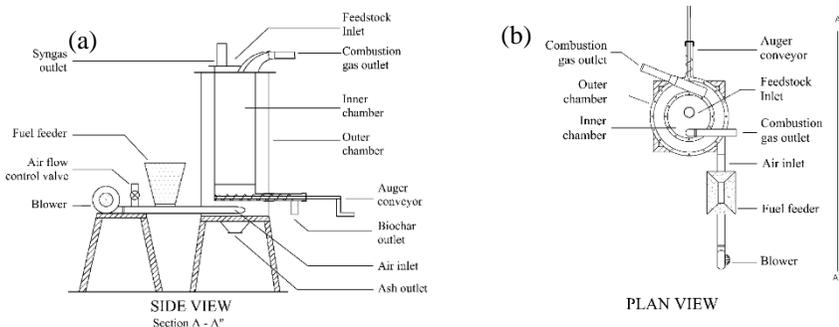
Figure 1. **(a) Cross section and (b) plan view diagrams of the Down Draft Double Chamber reactor**

Paddy husk was collected from the small-scale rice mills near *Kandy-Gampola (Gelioya* area), Sri Lanka. It was a mixture of paddy husk from different rice varieties. Other than that, coconut shells were used as a supplementary fuel source during the field trials.

Operation mechanism

This reactor was designed to manufacture biochar in continuous mode. During the field operations, the biochar production was done continuously and produced biochar was taken out approximately at 20 min intervals through the auger conveyor. The paddy husk resident time inside the reactor was approximately 30 minutes. The feeding of paddy husk was done batch wise when the inner chamber was emptied. The fuel paddy husk was fed continuously to the reactor after fluidizing with an average air supply of 0.01 m^3/s with a 4" air blower. Few coconut shells were added to the outer combustion chamber (0.77 kg/hr) in order to maintain the required temperature. The DDDC reactor together with the bubbling scrubber unit is shown in Figure 2.

Figure 2. The DDDC reactor during the field operations at Meewathura farm premises

Measurement of parameters

Reactor performance was assessed by measuring temperatures, conducting mass balance and analysing gas compositions during the field trials. Four K-type thermocouples were inserted to the outer chamber along the vertical axis of the reactor (Port 1 to 4, Figure 3) In addition, Campbell CR1000 data-logger was used for the temperature data recording. The composition and the energy values of syngas and exhaust gas were measured using a portable syngas analyser (Gasboard 3100P with 0.02–0.03% v/v precision). The measurement of gas was done by using three gas outlet ports (Figure 4). Ports 5, 6 and 7 were used to measure the exhaust gas, raw syngas measurement and cleaned syngas measurement, respectively. Volume% of constituents in exhaust and syngas such as CO, CO_2, O_2, N_2, CH_4, C_nH_m and H_2, and composite heating value (MJ/m^3) were frequently recorded.
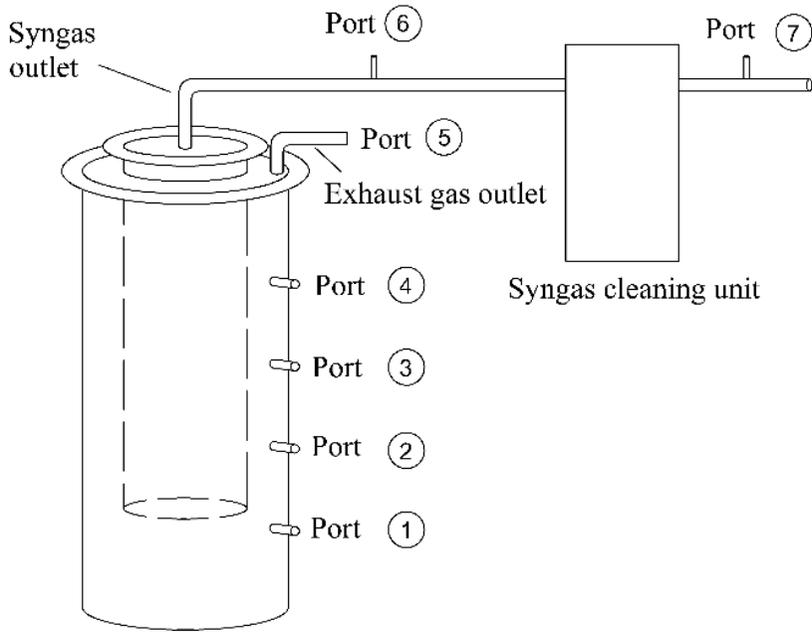
Figure 3. Thermocouple placement and syngas measuring ports in the DDDC reactor

The biochar recovery and the energy calculations were done by using the following equations.

$$Biochar\ recovery\ (\%) = \frac{Weight\ of\ obtained\ biochar\,(g)}{Weight\ of\ the\ used\ biomass\,(g)} * 100 \ \dots\dots\dots\dots\dots\dots\dots\dots\dots..(1)$$

Energy content of each biomass material used was evaluated from the equation 2 and the energy balance (equation 3) was used to estimate the energy losses through the reactor.

$$\begin{bmatrix} Energy\ content\ of \\ biomass\ material\ (kJ) \end{bmatrix} = \begin{bmatrix} Heating\ value\ of \\ the\ material\ (kJ/kg) \end{bmatrix} \times Used\ mass\ (kg) \ \dots\dots\dots\dots\dots\dots\dots..\dots(2)$$

$$Q_{Input} = Q_{output}$$

$$\begin{bmatrix} Energy\ in \\ Feedstock \end{bmatrix} + \begin{bmatrix} Exetrnal\ energy \\ from\ fuel \end{bmatrix} = \begin{bmatrix} Energy\ in \\ biochar \end{bmatrix} + \begin{bmatrix} Energy\ in \\ gaseous\ products \end{bmatrix} + \begin{bmatrix} Energy\ in \\ Bio-oil \end{bmatrix} + [Losses] \ \dots..(3)$$

RESULTS AND DISCUSSION

Temperature variations

The temperature data obtained from the reactor during the field trials showed a gradient of the temperature from bottom to the top of the reactor where there was an average temperature of 560 °C near the bottom of the reactor and an average temperature of 330 °C near the top of

the reactor (Figure 4). The temperature requirements for the different stages of the pyrolysis process and their relationship with the reactor operating mechanism are given in the Table 2. Accordingly, the temperature gradient of the reactor fulfilled the temperature requirement to complete the different stages of the pyrolysis process.
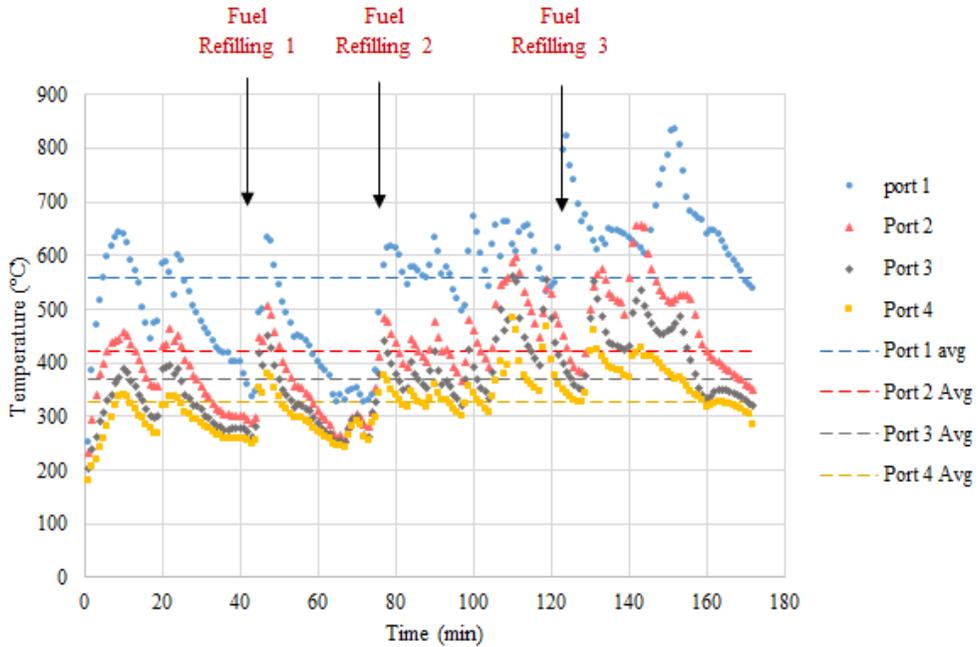
Figure 4. Temperature variations of the DDDC reactor

Table 2. Temperature requirements for different stages of the pyrolysis process (Basu, 2013)

Pyrolysis stage	Process	Required temperature (°C)	Port No	Avg. reactor temperature (°C)
Drying stage	Removal of H_2O	100 – 150	4	330
Initial stage	Removal of H_2O and low-molecular weight gasses like CO and CO_2	100 – 300	3	370
Intermediate stage	Production of char, bio-oil and non-condensable gasses	200 – 600	2	425
Final stage	Secondary cracking of volatiles occur producing secondary char	300 – 900	1	560

Although the average temperatures gradient within the combustion chamber was adequate for the pyrolysis process, the results indicated fluctuations of temperature during operation due to incomplete combustion of paddy husk used as the fuel source at bottom stationary layers

(Figure 5). Further, half-burned paddy husks were observed in the ash. Consequently, an additional high energy fuel supply, coconut shell (0.77 kg/hr) was required to maintain optimum temperatures for the pyrolysis process. Hence, maintenance of a thick coconut shell charcoal layer at the bottom of the combustion chamber could be suggested to minimize temperature fluctuations observed during the pyrolysis process.

Syngas composition and energy value

The summery of the obtained syngas analysis results are shown in the Table 3. The total volume of combustible gasses (CO, CH_4 and H_2) was 33.57% in the cleaned syngas. The average calorific value was 5.58 MJ/m^3, which was higher than the value reported (5.13 MJ/m^3) by Atae, *et al*. (2012). High energy content of the produced syngas increases its ability to use as a fuel. Also, the low amount of O_2 is desirable in industrial operations as it reduces the probability of explosions (Kate and Chaurasia, 2018).

Table 3. Summary of the syngas analysis data

Gas type	CO (%v/v)	CO₂ (%v/v)	CH₄ (%v/v)	CₙHₘ (%v/v)	H₂ (%v/v)	O₂ (%v/v)	N₂ (%v/v)	Calorific Value (MJ/m³)
Exhaust gas	0.64 (±0.35)	7.21 (±0.21)	0.66 (±0.05)	0.00 (±0.01)	0.00 (±0.18)	12.23 (±0.22)	79.26 (±0.34)	0.34 (±0.08)
Raw syngas	20.78 (±0.74)	13.30 (±0.29)	3.87 (±0.10)	0.30 (±0.01)	6.91 (±0.26)	0.68 (±0.42)	54.16 (±0.95)	5.34 (±0.18)
Syngas after cleaning	22.76 (±0.10)	11.27 (±1.08)	3.78 (±0.03)	0.31 (±0.00)	7.03 (±0.00)	0.71 (±1.18)	54.14 (±0.2)	5.58 (±0.02)
Ref. 01	11.51	21.43	-	-	30.78	-	35.27	5.13
Ref. 02	42.79	30.05	0.00	-	27.16	0.00	-	-

Note: standard deviations are provided in brackets, Ref. 01: (Ataei, *et al.,* 2012), *Ref. 02:* (Kate and Chaurasia, 2018)

It was also observed that the absorbance of CO_2 by the bubbling scrubber decreased CO_2 percentage from 13.3 (% v/v) to 11.27 (% v/v), which increased the concentrations of useful combustible gasses in the gas mixture. There is a 0.09% reduction of CH_4 in the $Ca(OH)_2$ treated syngas and this could be due to the variation of measured values as mentioned in the Table 3. Additionally, there is a slight water solubility of CH_4, though there are no any ionic reactions.

Biochar recovery and the mass balance of the reactor

The average biochar recovery of the reactor was 31.75% (dry basis). Natarajan and Ganapathy (2009) reported that average char yield at 550 °C is about 34% and Hsu*, et al*., (2015) reported average char yield of 30.65% at the temperature 600 °C and at a feeding rate of 10 g/min. Thus, the obtained results were within the satisfactory level. The average mass generation/consumption rates obtained during the field trials are given in Table 4. The average moisture content of the used paddy husk was 10% (wet basis). The mass generation

rate for the bio oil was calculated referring the oil recovery percentage of 38.8% for rice husk (Islam, *et al.*, 2011). Syngas yield was calculated assuming all the remaining mass of the feedstock turned into gaseous products. The obtained average biochar production rate was 1 kg/hr by consuming 4.42 kg of paddy husk and 0.77 kg of coconut shell per hour as fuels.

Table 4.   Mass balance for the DDDC reactor

	Material	Avg. Mass consumption/ generation rate (kg/hr)
Inputs	Feedstock (Paddy husk)	3.5
	Fuel (Paddy husk)	4.42
	Fuel (Coconut shell)	0.77
Outputs	Biochar (31.75% recovery)	1
	Syngas (29.45% recovery)	0.92
	Bio oil (38.8% recovery)	1.22
	Water vapour	0.35

Energy balance of the reactor

The calorific value of each feedstock and fuel materials were obtained through literature data (Ma *et al.,* 2015; Islam *et al.,* 2011) and the syngas calorific value was obtained through direct measurements (Table 3). The table 5 shows the energy content of each material calculated using the equation 2.

Table 5.   Energy values for each biomass material in the pyrolysis process

Material	Mass flow rate (kg/hr)	Calorific value[†] (MJ/kg)	Energy content (MJ/hr)
Dry feedstock (Paddy husk)	3.15	12.85	40.48
Dry fuel (Paddy husk)	3.98	12.85	51.14
Fuel (Coconut shell)	0.77	20.80	16.02
Biochar	1.00	12.35	12.35
Bio-oil	1.22	16.00	19.52
Syngas	0.92	5.34	4.91

[†] Source: Ma *et al.,* (2015); Islam *et al.,* (2011)

According to the above data, the energy balance calculation was done with 60% and 80% combustion efficiencies for rice husk and coconut shells, respectively. By substituting the respective values for the equation 3, energy loss through the reactor was calculated as below.

$$[40.48] + [(51.14 \times 0.6) + (16.02 \times 0.8)] = [12.35] + [4.91] + [19.52] + [\text{Losses}]$$
$$\text{Energy loss from the reactor} = 47.2 \text{ MJ/hr}$$

The energy losses through the reactor accounts 56.2% of the total energy input, which can be reduced by proper insulation with high temperature ceramic concrete cover.

CONCLUSIONS

A novel Downdraft Double Chamber pyrolysis reactor (DDDC) was designed and successfully tested for continuous operation to produce paddy husk biochar and syngas. The performance evaluation showed a satisfactory biochar recovery rate (31.75%) and syngas energy value (5.53 MJ/m^3). The major issue with the reactor was the temperature fluctuations occurred during the continuous operations due to low energy value of paddy husk and high energy losses. The mass and energy balance assessment suggested that proper insulation, change of fuel: air ratio and maintenance of a thick charcoal bed at the bottom of the combustion chamber could contribute to maintain a constant temperature during continuous operations. Thus, the design and testing of pilot scale DDDC reactor showed the potential of optimizing and upscaling a continuous mode paddy husk pyrolysis reactor for industrial applications.

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