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Published in:
Energy Procedia

DOI:
10.1016/j.egypro.2019.01.303

Publication date:
2019

Citation for published version (APA):
Kamble, P., Khan, Z., Gillespie, M., Farooq, M., McCalmont, J., Donnison, I., & Watson, I. (2019). Biomass gasification of hybrid seed Miscanthus in Glasgow's downdraft gasifier testbed system. *Energy Procedia*, *158*, 1174-1881. https://doi.org/10.1016/j.egypro.2019.01.303

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 158 (2019) 1174–1181

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018,

Hong Kong, China

Biomass gasification of hybrid seed *Miscanthus* in Glasgow's downdraft gasifier testbed system

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Abstract

Global energy problems, rise in CO_2 emissions and their implications on climate change are well documented. Renewable energy provides a crucial role in reducing these emissions whilst providing sustainable energy; energy conversion of biomass forms a valuable part of a renewable energy portfolio, with capability for baseload provision, and gas and electricity production. Gasification is the thermochemical conversion of biomass (carbonaceous material) into producer gases. A small-scale throated downdraft gasifier was designed and manufactured at the University of Glasgow and built to easily assess the gasification performance under different conditions e.g. feedstock variety and with different instrumentation and control strategies. Various feedstock varieties of *Miscanthus* (OPM12, MxG, and OPM53) were gasified under the same equivalence ratio (ER 0.30). The elemental compositions of each *Miscanthus* varied with their genetic properties. A Gasifier Control Unit (G.C.U) was installed on the experimental gasifier to measure parameters: temperature, pressure, liquid flow and mass flow. The gasifier was operated in batch mode; to improve repeatability the throat, grate and assembly were cleaned after each experiment. The experimental work reported in this research is mainly focused on the comparative study and analysis of the producer gas compositions, carbon conversion efficiency, higher heating value (HHV), lower heating value (LHV), cold gas efficiency and gas yield with the different biomass feedstocks. The ultimate and proximate analysis was done for all *Miscanthus* varieties along with ash analysis. The major outcome of this research was to investigate the impact of feedstock variety on gasification performance and identify preferred *Miscanthus* varieties to grow at scale with optimised gasification.

Keywords: Gasification; Downdraft Gasifier; *Miscanthus*; Ash analysis; Process optimisation.

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10.1016/j.egypro.2019.01.303

Nomenclature

BPS	Bits per seconds
ER	Equivalence Ratio
GCU	Gasifier Control Unit
HHV	Higher Heating Value
IDE	Integrated Development Environment
LHV	Lower Heating Value
LPM	Litres per minute
MSW	Municipal Solid Waste

1. Introduction

Biomass renewable energy derives from sunlight where chemical energy is stored in organic matter. Biomass fuels can be derived from energy crops, plants and trees, municipal solid waste (MSW) and agriculture waste. Generation of electricity or power from biomass can be achieved through combustion of gases derived from thermochemical processing, anaerobic digestion or direct combustion of the biomass and production of steam with subsequent electricity generation from a turbine.

Gasification is a thermochemical process that is used to extract useful gases from a variety of feedstock (e.g. coal, biomass and waste) which can subsequently be used to produce electricity from internal combustion engines or gas turbines, depending on the tar content of the gas. In updraft, fluidized bed and downdraft gasifiers, tar concentrations are typically produced around 20 g/Nm^3, 300 mg/Nm^3 and 54 mg/Nm^3 respectively [1]. If gasifiers are operated under optimal conditions, a clean syngas with low tar concentration can be produced reducing the need for subsequent gas cleanup which is often an expensive part of the feedstock to power conversion route.

Zainal *et al.* [2] found, initially, the calorific value of the producer gas increases with respect to increasing equivalence ratio (ER) up to a maximum point. Afterwards, the calorific value decreases with respect to increasing ER. This indicates that the ER cannot be set as the constant value for batch mode gasification processes. Kumararaja *et al.* [3] developed an experimental investigation into downdraft gasification with the gasification temperature below 700ºC. Condensation of tar can cause system blockages [4] but at a higher gasification temperature of 900ºC higher tar concentrations were found due to lignin decompositions [5]. The downdraft gasifier produces a low tar content in its emissions, therefore, the producer gas can be used directly in a combustion engine. However, system performance can benefit from online tar detection systems to monitor and optimise the gasification process. Other work by the authors relating to tar detection systems has been published previously [6].

Many studies have examined different aspects of gasification. For example, Prasertcharoensuk *et al.* [7] have published theoretical research on optimizing the production of hydrogen for a throated downdraft gasifier using Computational Fluid Dynamic (CFD) software; Lingqin *et al.* [8] experimentally found that the CO_2 concentration is higher than CO for biomass gasification in the fluidized bed gasifier with an oxygen-enriched reactant but few studies have developed control strategies for gasification.

The experimental work reported in this research investigates the downdraft gasifier performance with various genotypes of *Miscanthus.* The feedstocks (OPM12, MxG, and OPM53) of *Miscanthus* and elemental analysis were obtained from the University of Aberystwyth [9]. The laboratory-scale, ~3.4kW downdraft gasifier, was manufactured at the University of Glasgow. The in-house Gasifier Control Unit (GCU) and instrumentation were installed on the gasifier to measure temperature, pressure, mass flow and gas compositions [10]. The ER is key to controlling the stoichiometric reactions, which occur inside the gasifier; optimizing the ER allows better performance of the gasifier. After the gasification experiments, ash residues were analysed at the University of Leeds [11]. There is a research gap in addressing optimization procedures of downdraft gasifiers and identifying preferred feedstocks. This research investigates finding the optimum of conditions of the gasification phase and addresses the impact of the feedstock optimization on gasifier performance.

2. Materials and methods

Twelve K-type thermocouples were connected to different locations in the gasifier system, see Fig 1 [12]. Pressure sensors (P01) and (P02) were connected to the top of the gasifier and hot gas filter respectively. The red-y mass flow controller (MFC red-y smart, Vögtlin Instruments AG, Switzerland) was connected to the air inlet pipe of the gasifier [13] in the throat region. The setpoint for the red-y controller was changed automatically between the combustion or gasification mode. The producer gas (outlet) flow rate was measured and recorded with a Sensirion mass flow sensor (SFM 3000, Switzerland) [14].

The liquid flow was measured with a liquid flow sensor at the liquid collection point after the condenser. Various sensors have their own software for data acquisition and they also can work independently. It was, therefore, difficult to make automated feedback loop systems to optimise gasification using the company's proprietary software. The syngas sampling was done with an STG MCA 100 Syn Model (ETG Risorse E Tecnologia, Italy).

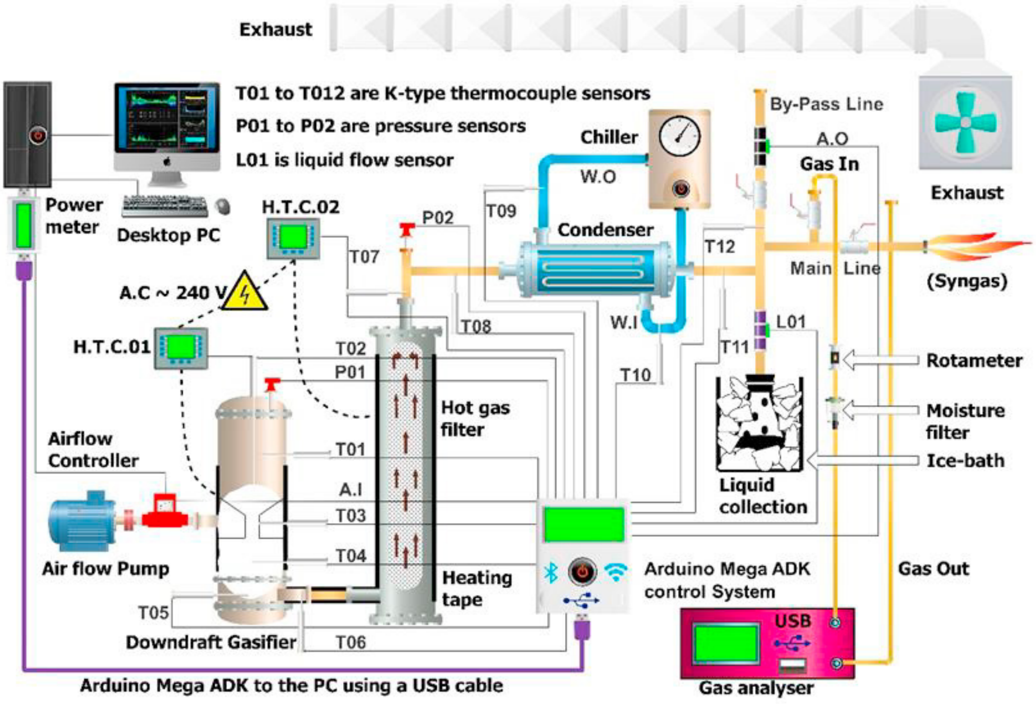

Fig 1 System diagram of the gasifier system: temperatures are measured at T01 (drying), T02 (pyrolysis) and T03 (throat), T04 (gasification), T05 (under the grate), T06 (exit pipe of gasifier), T07 (top of hot gas filter), T08 (inlet of condenser) and T09 (outlet of water from the condenser), T10 (inlet of water in to the condenser), T11 (inlet of liquid collections system) and T12 (outlet of producer gas), P01 (pressure at top of gasifier) and P02 (pressure at top of hot gas filter), L01 (liquid inlet), A.O (producer gas outlet), HTC01 (heating tape controller for gasifier) and HTC02 (heating tape controller for hot gas filter)

The sensors were calibrated under atmospheric conditions and connected to a single loop control system. The data from the sensors was collected with an Arduino Mega ADK microprocessor board. The Gasifier Control Unit (GCU) system successfully achieved automated control of the ER, set at a baud rate of 250000 bits per seconds (bps). The Arduino Mega ADK (R3) board was programmed in C++ and code was uploaded using Arduino software v 1.8.5 (IDE) [15].

In industry high-cost software and data acquisition and control systems are usually used e.g. SCADA for gasifier control. Another objective of this research is to reduce processing costs by using inexpensive equipment and deployment strategies. Previously Hitchner [16] interfaced systems between Arduino (IDE) and Microsoft Excel, that can be simply modified. In the current case, Arduino was connected to Microsoft Excel with a 1 sec delay which allowed rapid calculations e.g. mass balances. This allows a low cost and robust solution which can be easily deployed. Figure 2 shows the experimental setup for downdraft gasifier.

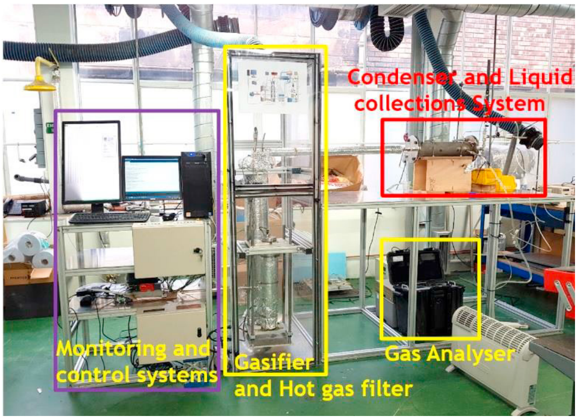

Fig. 2. Experimental setup for Glasgow's downdraft gasifier

The downdraft gasifier was wrapped in electric heating tape and initially heated up to 400ºC (T04, see Fig. 1) without *Miscanthus* or air supply. The *Miscanthus* (OPM12, MxG and OPM53) samples were weighed to 700g (100 + 600). 100 g was inserted into the system and a flow rate of 55 L/min was provided, once the biomass was ignited a further 600 g was introduced into the gasifier which was then sealed. Due to endothermic reactions, the *Miscanthus* absorbed heat from the gasifier and the temperature reduced from 400ºC (T04) to approximately 230ºC. At this point, the temperature begins to rise as exothermic reactions begin.

Once 400ºC was reached (3-5mins), the flow rate was automatically reduced to 14.44 L/min, at this point the current was turned off to the electrical tape around the gasifier. The maximum gasification temperature (T04) was ~1200ºC with a pressure of ~1.12 bar. Conveniently, the gasification experiments were completed within approximately 1-hour allowing multiple runs in the day. The reactions in downdraft gasifiers are well known and summarized below in Table 1 for convenience.

Table 1. Summarized Reaction in a downdraft gasifier

R:1	$C + \frac{1}{2} O_2 \rightarrow CO$	*-111 kJ/kmol*	Char partial oxidation reaction	[17, 18]
R:2	$C + O_2 \rightarrow CO_2$	-394 kJ/kmol	Total oxidation reaction	[17, 18]
R:3	$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$	-242 kJ/kmol	H_2 combustion reaction	[17]
R:4	$C + CO_2 \leftrightarrow 2CO$	+172 kJ/kmol	The boudouard reaction	[19, 20]
R:5	$C + 2H_2 \leftrightarrow CH_4$	-75 kJ/kmol	The methanation reaction	[17, 21]

The feedstock was converted into the producer gases: H_2, CO and CH_4 and liquid (mainly moisture, bio-oil or tar) samples. Raw gases were released from the gasifier and passed through the hot gas filter which was held at 350ºC with external electric heating tape. The filter was used to remove ash and other solid particle impurities. A real-time liquid collection system was installed after the condenser (Fig. 1). The producer gases were passed to the exhaust on the mainline connections and the mass flow rate was recorded (SFM3000, Sensirion, Switzerland).

3. Results and discussions

The gasification experimental procedure was repeated for the *Miscanthus* samples (OPM12, MxG and OPM53) with an ER value set at 0.30 and the results were examined to find the optimum gasification point in time during the run. Before the experiments, the ultimate and proximate analysis of the samples were found, see Table 2. The results compare favourably with Yengkhom *et al.* [22]. The volatile, fixed C, ash, C and H, N, S and LHV for each *Miscanthus* variety are almost the same but the moisture contents varied. The moisture content (%) and L.H.V (MJ/kg) for the *Miscanthus* samples OPM12, MxG and OPM53 compare favorably with results from Jayaraman *et al.* [23] and Bridgeman *et al.* [24].

Table 2. Elemental compositions of different genotypes of *Miscanthus*

Miscanthus	Ultimate analysis wt. (%)			Proximate analysis wt. (%)						LHV (MJ/kg)
	Moisture	Volatile	Fixed C	Ash	C	H	N	S	O^a	
OPM12	9.1	73.9	14.6	2.4	44.6	5.6	0.5	0.1	49.2	17.44
MxG	3.7	78.4	15.9	2.0	46.0	5.6	0.2	0.0	48.2	18.65
OPM53	6.2	76.3	15.0	2.6	45.0	5.7	0.6	0.1	48.7	18.03

Table 3 shows the gas compositions from gasification for the various genotypes of *Miscanthus* at the optimum time of gasification with respect to gas compositions. The gas compositions of H_2, CO and CH_4 (vol%) comparable with those results from Gnanendra *et al.* [25] and Khelfa *et al.* [26]. The gas compositions of CH_4 (0.22 Vol%) for gasification of OPM12 *Miscanthus* are lower due to a lost connection with the CH_4 sensor. The gas compositions changes are of course dependent on different gasification parameters e.g. E.R ratio, feedstock and thermochemical process [27, 28]. However, It also depends on the gasifier type and design such as throated or un-throated [28].

Table 3. Producer gas composition profiles

Miscanthus	CH_4 Vol (%)	CO Vol (%)	CO_2 Vol (%)	O_2 Vol (%)	H_2 Vol (%)	N_2 Vol (%)
OPM12	0.22	19.30	8.66	1.07	3.25	67.50
MxG	21.70	13.40	17.97	0.27	3.14	43.52
OPM53	16.58	15.36	16.65	0.74	6.50	44.17

Table 4 shows the average temperature and pressure values from the batch runs with different feedstocks. The results for OPM12 and MxG *Miscanthus*; the drying, pyrolysis and throat temperature are almost similar to the literature [29] but the gasification temperature shows a large difference of nearly 300 ºC. The gasifier is open to atmosphere so the gasifier and hot gas pressure are generally close to atmospheric. Interestingly, during the gasification of sample OPM12 the gasifier and hot gas filter pressures were less than atmospheric.

Fig.3 shows the product gas and system efficiencies (carbon conversion and cold gas) profiles with respect to time. The variation of both efficiencies (Fig.3(b)) can be clearly explained by the gas composition profile (Fig.3(a)). The slightly higher CO_2 concentration can be compared to the work reported by Kallis *et al.* [30] (12 vol%) for *Miscanthus* pellets in continuous mode of operation. However, the slight difference may be due to the batch mode of operation in the present study, which implies a constant air flow rate in spite of a fixed batch of feed. This condition allows high O_2 content in the gasifier as the mass of the biomass decreases continuously. Secondly, in continuous mode of operation, the equilibrium is established at a lower temperature which may explain the low CO_2 concentration in the study [30].

Table 4. Downdraft gasifier performance parameters

Miscanthus	Drying (T01) (ºC)	Pyrolysis (T02) (ºC)	Gasification (T04) (ºC)	Throat (T03) (ºC)	Gasifier pressure (P01) (bar)	Hot gas filter Pressure (P02) (bar)	Optimum time of gasification(minutes)
OPM12	219	380	985	430	0.99	0.97	12
MxG	268	427	725	497	1.05	1.08	30
OPM53	116	211	699	407	1.07	1.10	32

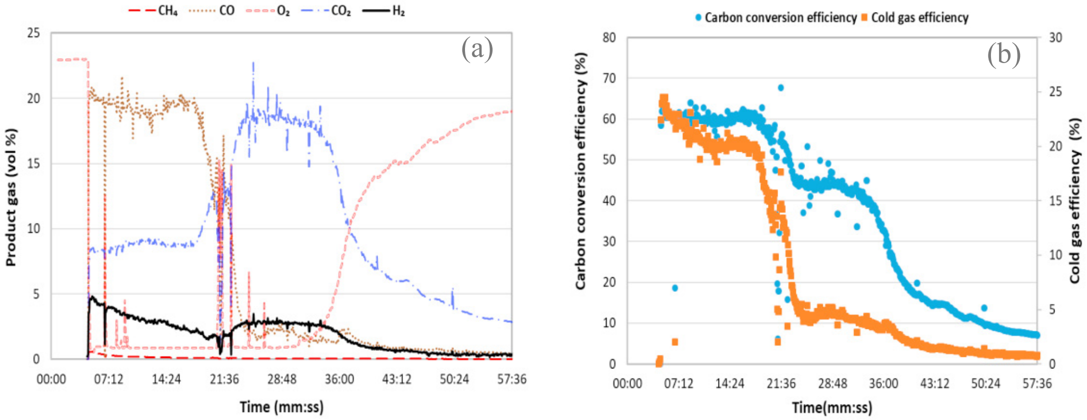

Fig. 3. OPM12 gasification; (a) product gas profile and (b) Carbon conversion and cold gas efficiencies profiles

Table 5 shows the experimental gasification results for gas yield (m^3/kg biomass), HHV (MJ/m^3), LHV (MJ/m^3), cold gas efficiency (%), Carbon conversion efficiency (%), ash residue (g), unburnt biomass (stuck in the gasifier, 22.48 g) and theoretical moisture; these results compare favourably with Zainal *et al.* [2] and Kamble *et al.* [31]. Among *Miscanthus* OPM12 has lower cold gas efficiency, LHV and HHV as compared with the results of other *Miscanthus* samples.

Table 5. Experimental results

Miscanthus	E.R	Gas yield (m^3/kg biomass)	HHV (MJ/m^3)	LHV (MJ/m^3)	Cold gas efficiency (%)	Carbon conversion efficiency (%)	Ash left (g)	Unburnt biomass (g)	Tar (g)	*Moisture (g) Theoretically
OPM12	0.30	1.24	2.94	2.87	21.00	61.36	14.81	0.00	41.30	63.70
MxG	0.30	1.94	10.73	9.80	58.37	86.28	11.12	22.48	87.10	25.90
OPM53	0.30	1.23	9.38	8.59	65.00	99.00	15.65	0.00	56.60	43.40

After gasification, the ash residues were analyzed at the University of Leeds, and the results can be seen in Table 6; standard analytical protocols were used [8, 31].

Table 6. Ash residues analyzed results

Miscanthus	mg/kg ash(ar)												
	Na	Mg	Al	Si	P	S	Cl	K	Ca	Cr	Mn	Fe	Ni
OPM12	3723	19906	4900	255456	16819	218547	1679	94361	130637	1013	3326	11662	471
MxG	3387	12625	3983	222567	26702	190409	1189	90926	166091	3842	1968	17735	931
OPM53	2233	18170	2501	249192	16602	213188	6585	102455	132923	1099	2818	8578	206

As can be seen from the table, the results for the different genotypes of *Miscanthus* at ER of 0.30 were similar. Notable exceptions include Cl, which was about 5.5 times lower for MxG than OPM53; Cr which was about 3.5 times higher for MxG than the other samples and Ni which was about 4.5 times lower for OPM53 compared to MxG and 2.2 times lower than OPM12.

4. Conclusion

The experimental investigation for different genotypes of *Miscanthus* with a downdraft gasifier test-bed, using the same equivalence ratio, found variation in the average gasification temperatures in the drying, throat and pyrolysis zones but the pressure differentials across the grate were similar. Clearly, the ER value needs to be optimized for each feedstock under batch conditions. The average producer gas compositions change with respect to the *Miscanthus* samples; which of course is not a steady state for batch operation. Downdraft gasifiers, operating in batch mode are a nonlinear process and current work is addressing real-time control systems to optimize the gasification process under these conditions to improve the carbon conversion efficiency and the gasifier stability. Future work is addressing the automatic feed of biomass at the optimal gasification point

Acknowledgements

The authors would like to thank EPSRC (EP/M01343X/1) and SUPERGEN Bioenergy Hub (UK) for funding this research. Prashant Kamble was kindly supported by a Government of Maharashtra scholarship for his PhD studies at the University of Glasgow (DSW/EDU/F.S/15-16/D-IV/1762).

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