Design, instrumentation, and operation of a standard downdraft, laboratory-scale gasification testbed utilising novel seed-propagated hybrid *Miscanthus* pellets

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Abstract

Biomass gasification remains an attractive option to impact climate chaos; however, the technology presents challenges in tolerance to feedstock variability and tar production, which can limit the overall process efficiency, gasifier performance, durability and downstream syngas utilisation. The primary objectives of this study were to compare two gasifier design approaches using different reaction kinetics, based on multiple or singular oxidation and gasification reactions, and build and test a novel, flexible, laboratory-scale downdraft gasifier to convert pellets from UK hybrid *Miscanthus* into syngas, whilst deploying inexpensive instrumentation methods The experimental gasification parameters studied were carbon conversion efficiency, gas yield, cold gas efficiency and gas heating values. The performance study shows that the system achieved good average temperature (842-866 ºC) in the reduction zones for equivalence ratios between 0.25-0.35. The optimum values for carbon conversion efficiency, cold gas efficiency, heating values (HHV) of product gas and gas yield were 74%, 32%, 4.17 MJ/m^3 and 1.32 m^3/$kg_{(biomass)}$, respectively. The reported performance parameters for the new seed-propagated hybrid Miscanthus in the present study were comparable to those from conventional *Miscanthus* pellet gasification in downdraft gasifiers but these new hybrid varieties offer advantages in productivity over broader climatic regions compared to conventional varieties.

1. Introduction

Biomass and bio-fuel research has increased recently due to its potential to mitigate adverse effects of fossil fuels on the environment and climate change. Gasification offers significant advantage for flexible energy vector production at scale to convert biomass into product gas, which itself can be converted into heat, electricity, biofuels or platform chemicals [1]. Coal-fed gasification has operated successfully, including using fixed bed, fluidized bed, entrained flow, plasma and rotary kiln reactors [2]. However, biomass gasification has been less successful due to tar and ash production. Downdraft gasifiers are regarded as most suitable for small scale operation (< 1 MW) as they are simple to fabricate and operate [3, 4] and importantly produce low tar (0.015–3$gN^{-1}m^{-3}$) in the product gas [5] which, with less cleaning requirements, makes it suitable for direct application (generating electricity from Internal Combustion Engines (ICE)). Throated type (Imbert) gasifiers are restricted to operation with a specific biomass type [6] and to reduce throat bridging, gasifiers often need a specific feedstock moisture content, typically < 20 wt% [7]. Large-scale operation (> 1MW) is generally better suited to moving bed gasifier designs [8].

The design, modification and improvements of downdraft gasifiers generally consider gasifier dimensions, air/reactant supply, biomass feeding rate, ash/char production and recirculation of product gas systems [3]. The design and construction of larger throat-type (>70 mm) downdraft gasifiers have been widely studied and implemented [9-11] and their design rely on empirical equations. There have been few studies on smaller, laboratory based systems, let alone a standardised approach to gasifier design. The development of a standard, laboratory-scale gasifier offers benefits such as being able to rapidly evaluate, identify and compare optimal scaling strategies and process improvements e.g., feedstock evaluation, tar reduction, syngas clean-up and upgrading, and assessment of novel catalysts in different laboratories.

Some limited work has been reported for small-scale downdraft throated gasifiers. For example, Shrinivasa and Mukund [12] developed an economical throated downdraft gasifier (≤ 40 mm) while extrapolating the curves based on empirical relationships. Dasappa *et al*. [13] developed different small gasifiers with a throat size range from 30-40 mm based on Shrinivasa and Mukund [12]. Sutar *et al*. [14] carried out non-linear extrapolation of the design curves while developing 2.5 and 4.5 kW_{th} gasifiers, with throat diameters of 20 and 30 mm respectively. Besides, Singh et al. [15] studied the effect of combustion and emissions characteristics of babool, chail, and mango in top-lit up-draft cookstove. The study reported less CO emissions in this system compared to conventional three-stone cookstoves. However, most of these small gasifier investigations were developed for household cook stove applications, fuelled by raw biomass and they have not been utilized for development purposes or as a test-bed in downdraft gasification. These reported studies work well with fixed throat sizes but offer no flexibility in throat size and other dimensions at laboratory scale.

The present study focuses on the development of a laboratory based, throated downdraft gasifier with a flexible sliding throat arrangement, allowing routes to process optimisation and translating these results to larger gasifiers. The work forms the basis of a much larger study to improve the control of gasifiers using fluorescent based tar detection systems (not reported herein) and developing the gasifier as a test bed for evaluation of new technology, control and process enhancement and feedstock variety. It is also proposed to use this system as a way of identifying feedstock behaviour and suitability in a “standardised” gasifier, allowing comparisons between feedstocks to be more easily identified at a global scale, where the gasifier designs are freely available.

The perennial grasses, particularly dedicated perennial biomass energy crops such as *Miscanthus* offer high energy yields and favourable input/output energy ratios when compared to annual crops [16]. However, research into *Miscanthus* has primarily focussed on the current commercial clone, *M x giganteus* (M×g) [17] and while there are currently around 7,000 ha of this hybrid being grown in the UK, the clonal nature of its propagation (rhizome production and translocation) significantly limits its capacity to be rapidly scaled to meet potential market demand. IBERS at Aberystwyth University, through the GIANT-LINK project, successfully bred a range of new seed-propagated interspecies hybrids of *Miscanthus* [18]. Results from these trials have demonstrated a wide range of biomass density, moisture content and quality at harvest time, all issues that need to be addressed in the process of turning a field crop into a viable economic bioenergy feedstock [19]. The work herein reports on the literature gap on gasification trials of these new seed-propagated hybrid *Miscanthus* varieties (OPM12) and compares performance to M×g from the literature.

A Gasifier Control Unit (GCU) was developed using low cost instrumentation and an Arduino microcontroller which was implemented to monitor and record the reactor's temperature, pressure and mass flows at different locations throughout the downdraft gasifier system. The performance of the gasifier was evaluated through temperature, pressure and mass flow profiles, product gas composition, gas heating values, cold gas and carbon conversion efficiencies using novel seed-propagated hybrid based *Miscanthus* pellets as the feedstock. A comparative study with the literature is provided in terms of heating values, cold gas and carbon conversion efficiencies to evaluate the performance of the gasifier.

2. Methodology and key design parameters

2.1 Laboratory scale downdraft gasification system

The downdraft gasification system, shown in Figure 1, comprises a throated downdraft gasifier, batch-fed from the top with the exhaust gas leaving below the grate. It is worth noting that small batch fed gasifiers are complicated by non-steady state conditions during gasification and a non-linear optimisation process. The air is supplied via 120 L/min air pump (Jebao

Company Ltd, China) accompanied with an air flow controller (Red-y smart controller, GSC-D9SS-BB13, Vögtlin Instruments, Switzerland) to adjust and control the air equivalence ratio (ER) in the range of 0.25-0.35. After gasification, the product gas was passed through a hot gas ceramic filter (60x1000 mm, Glosfume Technologies Limited, UK) to separate solid particles from the product gas. The gas containing tar, was then passed through the condenser, where the gas temperature was reduced to < 40 °C. The condenser was followed by the tar (liquid) collection system as shown in Figure 1, where a flow rate sensor and collection vessel were used. A gas sampling point, located at the exit of the gas flow meter, was connected to a gas analyser (MCA 100 Syn Portable, ETG Risorse E Tecnologia, Italy) equipped with Thermal Conductive Detector (TCD), Nondispersive Infrared (NDIR) and Electrochemical gas sensors. The TCD measures H_2 and provides an accuracy and precision of $\pm$0.5% (absolute) and $\pm$0.5% (absolute), respectively. Similarly, CH_4 and CO_2 is measured via NDIR and offers accuracy and precision of $\pm$1.0% (full scale) and $\pm$0.8% (full scale), respectively. Furthermore, O_2 is measured via Electrochemical sensors and provides an accuracy and precision of $\pm$0.1% (absolute) and $\pm$0.1% (absolute), respectively.

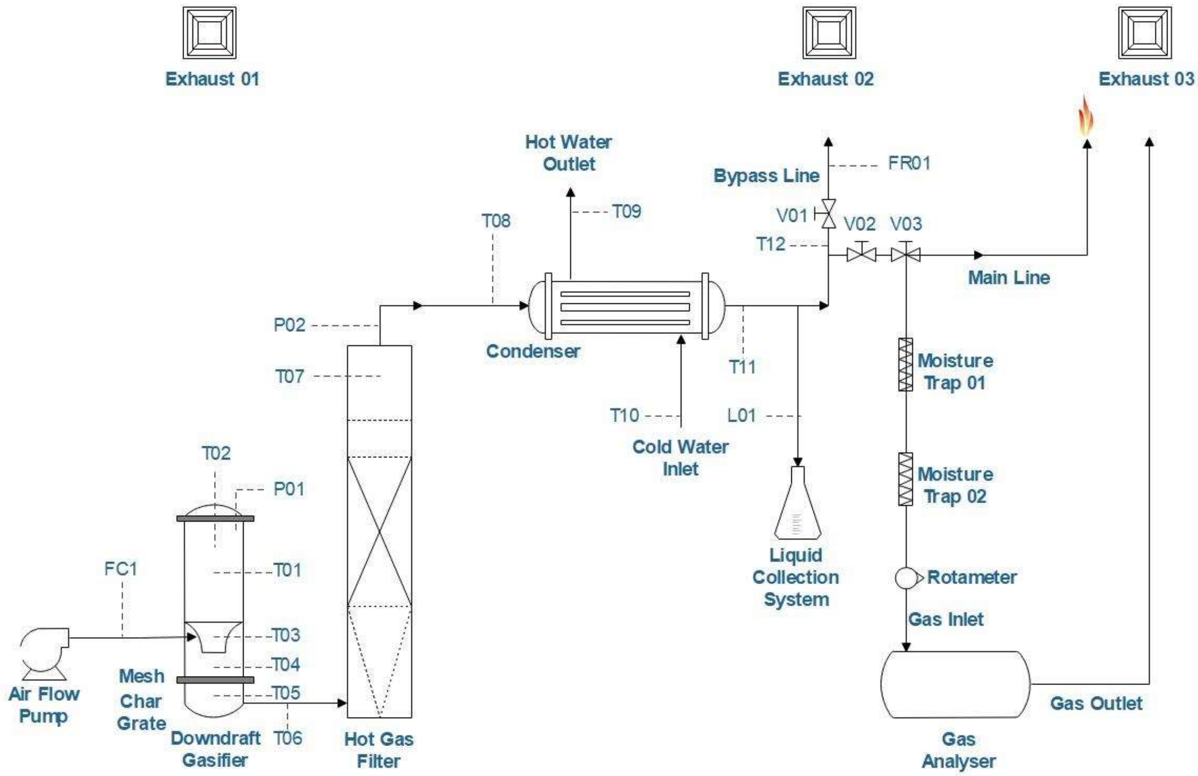


Figure 1. Schematic of downdraft gasification system, hot gas filter and condenser, showing the key instrumentation points (Temperature T1-12, type K thermocouples, pressure sensors P1-2, flow controllers FC 1-2, liquid collection system L01 and flame line FR01)

The ignition was initiated using a 270 W Eltherm (ELW-Q 0.7, UK) electrical heating tape located around the air inlet/throat on the gasifier, where typically the temperature was raised up to 400°C. A separate ignition port (just above the grate) was also provided to assist further with the ignition process if required. Initially, 100 g of biomass pellets (*Miscanthus*) were fed into the gasifier from the top of the system which was then sealed; air was injected (55 L/min) into the combustion region with ER = 1.0, via an air pump. Once the ignition was initiated, 600 g of biomass was subsequently added into the gasifier followed by re-sealing of the top flange and the process was switched to the gasification mode by reducing the air-flow rate to 14.30 L/min, resulting in an ER value of 0.30.

2.2 Instrumentation and control

Experimental data was collected automatically from the Arduino based GCU and from the instrumentation system at the points indicated in Figure 1 [20]. The temporal data was captured at 1 Hz and plotted in Excel because of the simplicity of this data capture method; given the relatively slow rate of change of the measurands this collection frequency was deemed as a sufficient resolution and conveniently reduced the data set size. The temperature of the gas was measured downstream at the inlet (T06) and outlet (T08) of the hot gas filter and either side of the condenser, where the inlet (T10) and outlet (T09) water temperature were also measured.

The measurements of temperature, pressure and liquid flow (mixture of water and tar) were centred around an Arduino (Mega ADK) microcontroller board, which has 16 analogue and 54 digital inputs and outputs (I/O). The microcontroller board was interfaced with a PC [21]. Twelve K-type thermocouples were distributed at different locations around the gasifier system and interfaced with Max 31855 breakout amplifier boards, which work with any K-type thermocouple sensor, with an accuracy of either ±2 °C (<700 °C) to ±6 (> 700) and with a resolution of 0.25ºC. The thermocouples were placed within the gasifier in the drying (T01), pyrolysis (T02), middle of the throat (T03), and bottom reduction (T04, above the grate) zones and below the grate (T05), as shown in Figure 2. The hot gas filter has an additional thermocouple (T07) as shown Figure 1 which was used to control the temperature of the heating tape to maintain the filter's temperature at 350 °C and to avoid any tar condensation on its surface [22]. The remaining thermocouples were located at the exit of the gasifier (T06), at the exit of the hot gas filters (T07), before (T08) and after (T11) the condenser, at the cold water inlet (T10) and at the hot water outlet (T09) linked to the condenser. A thermocouple (T12) was attached to the exhaust pipe of the product gas. All thermocouples were from Tempco

Electric Heater Cooperation, USA). All the thermocouples used were K-type (mineral insulated) and came with glass fibre stainless steel braided extension leads.

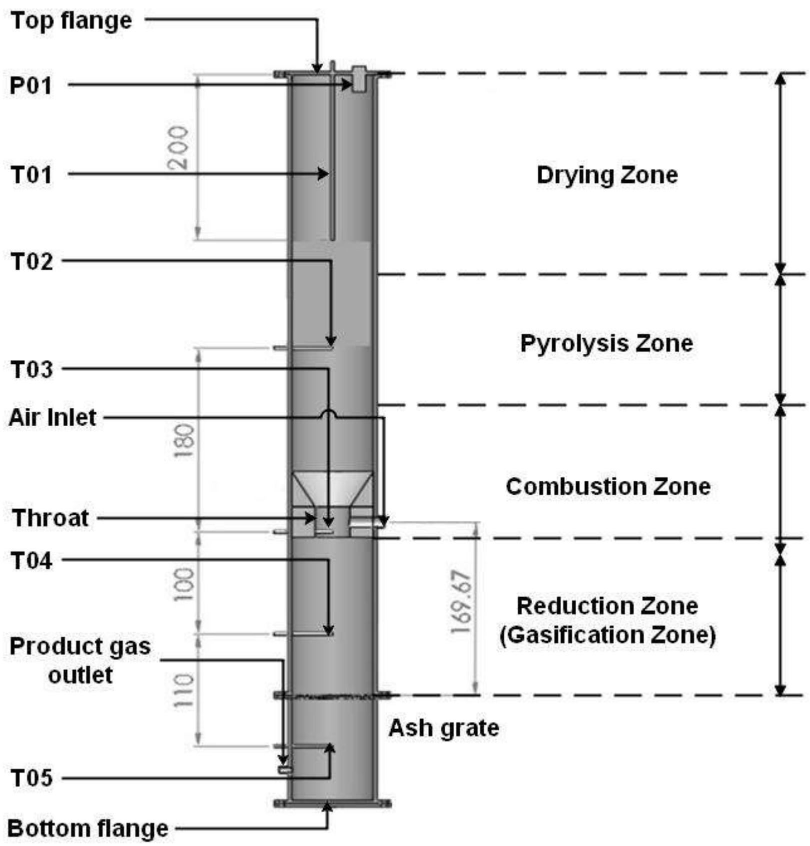


Figure 2. Downdraft gasifier with pressure and temperature measurements (all dimensions are in mm)

The Max 31855 amplifier I/O five pins, CLK, DO, CS, VIN, GND and the liquid flow sensor has three I/O pins, VIN, GND, and the output was interfaced with the Arduino Mega ADK microcontroller. The amplifier MAX31855 has its own library which was installed in the Arduino software (IDE V 1.8.1) [23].

2.3 Operating parameters

Initially, for the downdraft air gasification system the ER was the main optimisation parameter as the temperature variation in the system depends on this value and oxygen concentration. The ER can be defined as the ratio of $(A/F)_{actual}$ to $(A/F)_{stoich}$ where A and F represents the air and fuel flow rates for the actual flow rates used and stoichiometric value, respectively. For optimum ER design values, many researchers [9, 24, 25] argue that as the ER values increases, the gas calorific value first increases (around or close to ER=0.30) and then decreases, while tar removal is enhanced by increasing the ER. Based on this argument, the present study considers ER = 0.3 as an optimal design value for gasification, which was consequently used to design the throat diameter.

2.4 Gasification of new seed-propagated hybrid *Miscanthus*

The biomass properties define the feedstock total carbon content, which is an initial criterion to assess the total oxygen requirements for the gasification process. *Miscanthus* OPM12 was considered to initiate the design process. The total carbon content can be further divided into volatiles and fixed carbon which are pyrolysis products, these further react with oxygen in the air and can be converted into lighter gases. Similarly, the volatile content defines the reactivity of the biomass sample. The physical properties of the samples under this work are given in Table 1. The proximate and ultimate composition analysis of the biomass samples were found according to EN 14780:2011 standard for solid biofuels, total moisture and ash content were found following EN 14775:2009. From Table 1, the *Miscanthus* OPM12 is genetically different from the conventional variety of *Miscanthus* × *giganteus* (M×g) in terms of growth habits, maturation time, harvest, moisture content and stem density. However, the properties from proximate and ultimate analysis and its higher heating value (HHV) do not show much variation with M×g, as shown in Table 1. The N and S are substantially different (factor 2 and 10 times higher in OPM12 respectively) but still low in both cases (<<1%).

The *Miscanthus* OPM12 pellets are 5-6 mm in diameter with an average length in the range of 15-20 mm. The pellet size was especially important in determining the throat size, which is the smallest diameter within the gasifier, to avoid blockages or flow restriction.

Table 1. Proximate and ultimate analysis of new seed-propagated hybrid *Miscanthus* pellets OPM12 compared to M×g

	OPM12	M×g[a]
Proximate analysis (wt. % dry basis)		
Moisture	9.10	3.70
Volatile matter	73.90	78.40
Fixed carbon	14.60	15.90
Ash content	2.40	2.00
Ultimate analysis (wt. % dry basis)		
C	44.61	46.00
H	5.68	5.63
N	0.46	0.23
S	0.11	0.01
O (by difference)	49.24	48.16
Higher heating value (MJ/kg)	17.40	18.65

[a]Note: The different properties are listed here for comparison purposes and are not considered further for design evaluation and experimental investigation.

2.5 Flowability of new seed-propagated hybrid *Miscanthus* pellets

Maintaining flowability of *Miscanthus* pellets (diameter 6 mm and length 16-17 mm) through the throat and avoiding bridging is important for maintaining gasification. In the current case the angle of repose and the Hausner ratio were measured. The angle of repose test method used a funnel (300 mL) as suggested by Wu *et al*. [26], with 29 mm outlet diameter. Once filled, the funnel was raised to 17.5 cm above the ground and the average radius of the pile, r, was determined. The angle of repose, α, was calculated using the following relationship:

$$\alpha = \tan^{-1}\left(\frac{h}{r}\right)$$

Where h is the pile height. The Hausner ratio was determined from the ratio of the tapped to bulk density of the pellets. The bulk density was measured according to ASTM (standard 1895) and the tapped density was measured by lifting a graduated cylinder up by 10 cm and dropping it to collide with the surface on which it was originally placed. This was repeated 5 – 10 times until the sample volume was constant. The volume was noted, and the mass having previously been measured, allowed the tap density and Hausner ratio to be determined.

2.6 Gasifier design strategy

With the lack of commercially available gasifier design software, the aim of the design process is to evaluate different dimensions through empirical relationships formulated through experimental data. The two important dimensions to evaluate were the throat diameter, the smallest dimensions in the gasifier, and the diameter of the gasifier. The throat diameter is an important parameter which controls the gasifier efficiency [27] and has significant impact on syngas formation through major reactions (e.g., Boudouard and water gas reactions) [28].The throat diameter design strategy is shown in Figure 3; here the important design parameters were the hearth load and gasification rate, which was taken as 170-200 kg m^{-2} hr^{-1} and scaled down appropriately to define the diameter of the gasifier along with total gas produced through oxidation and gasification reactions (scheme 1 or 2), based on the biomass proximate and ultimate properties. This allowed calculation of the throat and reactor diameters, from which the design objectives were validated.

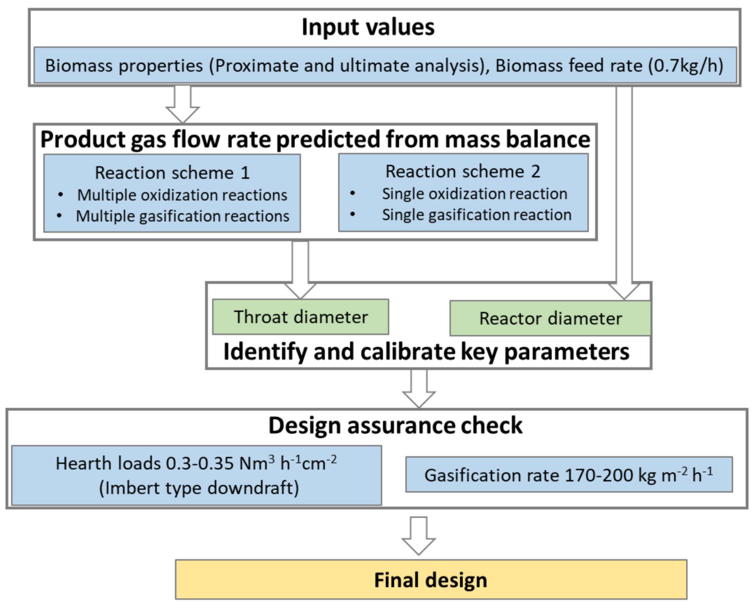


Figure 3 Design strategy for downdraft gasifiers

The feed is introduced from the top of the gasifier in batch mode and air in the throat region (Figure 1). As the feed drops down the gasifier, it decomposes and produces light components, which further react at different stages to produce the final product gas mixture and tar. The biomass passes through pyrolysis, oxidation and reduction zones to complete the decomposition process. However, the final gas product passes through a grate to react further with the mixture of char and ash at high temperature (700-950 ℃) to thermally crack tar into lighter gases. The following reaction combinations are considered, out of which reactions (4) and (5) are endothermic:

Oxidation reactions

- $C + O_2 \rightarrow CO_2$ ΔH=-394 MJ/kmol (1)
- $H_2 + 0.5O_2 \rightarrow H_2O$ ΔH=-242 MJ/kmol (2)
- $CH_4 + 1.5O_2 \rightarrow CO + 2H_2O$ ΔH=-891 MJ/kmol (3)

Reduction reactions (gasification reactions)

- *Boudouard reaction*

  $C + CO_2 \rightarrow 2CO$ ΔH=+172 MJ/kmol (4)

- *Water gas reaction*

  $C + H_2O \rightarrow CO + H_2$ ΔH=+131 MJ/kmol (5)

The total air required and product gas flow rate at a specific ER ratio were evaluated through the reactions scheme 1 (considered reactions from Equation 1 to 5) and reactions scheme 2 (only single gasification reaction as Equation 6,) and combustion reactions as Equation 7).

<u>Reactions scheme 1</u>

- The char was assumed to be produced by the fixed carbon content of the biomass given from the proximate analysis [29] and C participates in the oxidation reaction (1) [30] to produce one portion of the oxygen required for the gasification process (CO_2).
- The inherent hydrogen content in the biomass, from the ultimate analysis, participated in the oxidation reaction (2) to produce water or steam.

- Methane was assumed to be the sole volatile component generated from biomass decomposition. It was evaluated from the difference of total carbon and the fixed carbon which produced the methane oxidation reaction from reaction (3) forming CO and water or steam.

- The carbon dioxide and water produced by the oxidation reactions reacted with char in the reduction reactions (4) and (5) to produce carbon monoxide and hydrogen.

Reactions scheme 2

An alternative approach to Reactions Scheme 1 is to consider just a single general gasification reaction rather than complex reactions (1)-(5) to evaluate total gas flow rate. The molecular formula of *Miscanthus* OPM12 ($C_{3.74}H_{5.56}O_{3.10}$) was derived from Table 1 and the following combustion and gasification reactions were considered for (reaction scheme 2).

Gasification reaction

$$C_{3.74}H_{5.56}O_{3.10} + 0.46O_2 \rightarrow CO_2 + 1.74CO + 0.5H_2 + CH_4 + 0.28H_2O \quad (6)$$

Combustion reaction

$$C_{3.74}H_{5.56}O_{3.10} + 3.58O_2 \rightarrow 3.74CO_2 + 2.78H_2O \quad (7)$$

In the present study, both reaction schemes (1 and 2) above were used in assessing the gasifier design and almost no variation was found in the theoretical product gas flow rate produced using these two methods; 2.79 Nm^3 was generated through multiple reactions (reactions scheme 1) and 2.35 Nm^3 was produced via the single reaction approach (reactions scheme 2).

2.7 Throat diameter and air nozzle

Hearth load (superficial velocity) or the specific gasification rate were the key parameters used to determine the throat size of the gasifier as these determine the gasifier performance, controlling gas production rate, gas heating values, fuel consumption rate, and char and tar production rate [31]. Hearth load is defined as the total gas produced per unit cross sectional area of the throat. The reported values of hearth load for downdraft gasifiers are in the range of 0.09-0.9 Nm^3 hr^{-1} cm^{-2} [32] where low values represented the lowest pyrolysis temperature (600℃) which produced a large amount of char and tar in the product gas. Similarly, high values correspond to a high temperature (1050℃) which enables very high reaction rates between the product gas and less char-ash in the mixture but the product gas has a lower energy content [31]. Therefore, the present gasifier design considers a medium hearth load value of 0.3 Nm^3 hr^{-1} cm^{-2} which represents an Imbert (single throat) type downdraft gasifier, which typically have values of 0.3-0.35 Nm^3 hr^{-1} cm^{-2} [33]. For throat angle, Venselaar [15] compared design characteristics of several gasifiers and recommended a throat angle in the range of 45-60°. Sivakumar *et al*. [16] reported that conversion efficiency greatly increased at lower angles (45°) but decreased at larger values (90°). Moreover, Ojolo and Orisaleye [14] further added that the optimum inclination angle should be in the range of 45-60° for suitable downdraft gasification operation. The present design considered a removable annulus for the throat angle, so that it can be easily modified to any desirable angle, 60º was chosen for this work.

Once the reactor diameter was evaluated, the air nozzle area can be determined by the ratio of nozzle flow area to throat area [34]. This ratio was found to be 0.075 based on Sutar *et al*. [14] and nonlinear extrapolation data for small gasifiers. For nozzle angle, Sivakumar *et al*. [35] found that the nozzle inclination of 15º provides better results than 0 and 30º. The present design uses a nozzle cone angle of 15º.

There is a limitation of fuel particle size based on the throat size of the downdraft gasifier to avoid bridging. Kaupp and Goss [36] suggested that the maximum ratio of the throat to the diameter of fuel should be 6.8:1. Based on these observations, the size of the *Miscanthus* pellets with a mean diameter of 5-6 mm was nearest to the allowable limit stated.

2.8 Gasifier dimensions

The diameter of the gasifier was based on the gasification rate of biomass (kg) per unit cross sectional area of the reactor per unit time, as shown in Figure 2. Due to the unavailability of data (e.g. gasification rate) at the time of design for the gasification rate of *Miscanthus* species used in this work, other biomass such as rice husk were considered. Tianggo *et al*. [37] reported that the cold gas efficiency increased with increasing gasification rate in the range of 100-200 kg m^{-2} h^{-1}. Beyond 200 kg m^{-2} h^{-1}, the cold gas efficiency decreased with increasing gasification rate; consequently, they identified the optimum gasification rate as 200 kg m^{-2} h^{-1}, which was used in the present design. However, the evaluated diameter of the gasifier was verified based on the observation of Reed and Das [7] which stated that the diameter of the pyrolysis zone should be about twice that of the throat diameter, this observation was found to be the case in this design, as shown in Table 2. The gasifier height can be calculated based on the cross-sectional area and volume of the gasifier. The volume of the gasifier was estimated based on the volume of biomass occupied by a cylindrical volume of the reactor, which was calculated from the bulk density of *Miscanthus* grass (693±2 kg/m^3) and mass flow rate (or mass in batch operation).

2.9 Performance Parameters

A few key performance parameters: Higher Heating Value (HHV_g), Cold Gas Efficiency (CG_η) and Carbon Conversion Efficiency (CC_η) are considered to evaluate the downdraft gasification system.

HHV of the product gas in MJ Nm^{-3} can be determined by the equation [38]:

$$HHV_g = \frac{12.75 \times H_2 + 12.63 \times CO + 39.82 \times CH_4}{100} \quad (8)$$

Where CO, CH_4 and H_2 are the volume percentages of carbon monoxide, methane and hydrogen, respectively.

CG_η is defined as the ratio of energy of the gas to the energy in the fuel [39] and given by

$$CG_\eta = \frac{G_y \times HHV_g}{HHV} \quad (9)$$

Where HHV_g, HHV and G_y represents the heating values of gas (MJ/m^3), fuel feedstock (MJ/Kg) and gas yield ($m^3/kg_{biomass}$), respectively.

CC_η is the ratio of carbon in the product gas to the carbon content in the feedstock (C) [40],

$$CC_\eta = \frac{12 \times G_y \times (CO + CO_2 + CH_4)_g}{22.4 \times C} \times 100 \quad (10)$$

3. Results and Discussion

3.1 Downdraft gasifier-configuration and fabrication

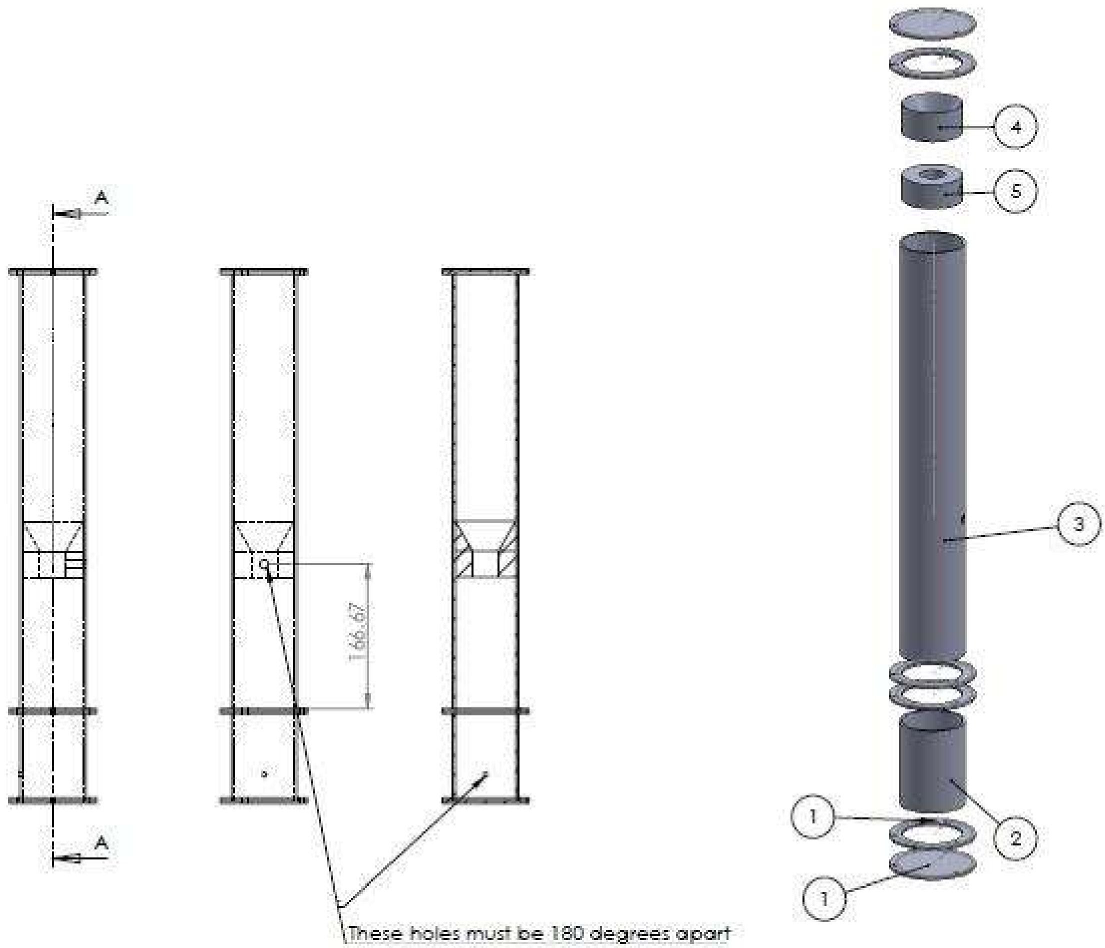
The gasifier was constructed from Stainless steel (SS) 310 due to its resistant capabilities to oxidation at high temperature (T >1000 °C) [41]. In addition, the air nozzle, flanges, and grate were fabricated from SS 310. The final operating conditions, design rating and basic design specification of the gasifier are shown in Table 2 below.

Table 2 Design specification of downdraft gasifier

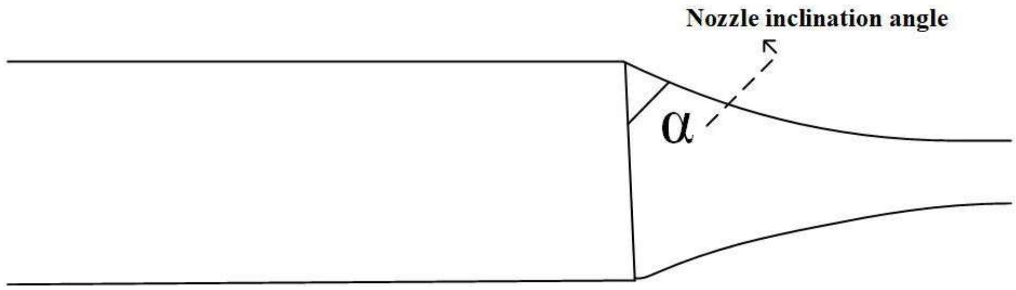
Parameter	Value
Material of construction	Stainless steel S310

Design rating	3.4 kW
Biomass feed, batch	0.7 kg (0.7 kg/h)
Air flow rate (0.20-0.40 ER)	0.87-1.3 kg/h
Gasifier diameter (ID)	70 mm
Gasifier height (with flanges)	720 mm
Throat diameter	30 mm
Throat height (with annulus)	60 mm
Throat angle	60°
Grate diameter (ID)	70 mm
Nozzle diameter	10 mm
Nozzle Cone half-angle of,	15^{o}
Number of nozzles	1
Orifice size (grate, 43% open)	2 mm

The 3-D design work was created in SolidWorks 2014. The fabrication of the downdraft gasifier was done in-house at the University of Glasgow, School of Engineering workshop and split into five different parts, as shown in Figure 4. It mainly consisted of the bottom (1 and 2) and top parts (3, straight geometry; 4, angle insert or cone side of the throat and 5, annulus support). The top part was further divided into the straight cylinder (part 3, 500 mm long) and throat geometry (part 4; 5). The lower part 2 contains the grate and connecting flanges. The throat rests on top of the annulus and it can be easily replaced with other designs for optimization; figure 4 shows photographs of the nozzle. The air nozzle dimensions are related to the throat diameter through empirical relationships and with the present design, the air nozzle can be easily changed or modified with respect to the throat configuration. The grate is an important part of the gasifier assembly, which effectively enables tar cracking when gasification products pass through a mixture of char-ash built up on the grate. The grate is flanged between parts 2 and 3 (just below the reduction zone) of the gasifier and it is easily replaceable with different mesh sizes, see Figure 2 and Table 3 for dimensions. The gasifier was simple to assemble and operate. The 3 mm mesh thickness was a potential weakness and cracked after about 20 runs. A greater thickness would be recommended.

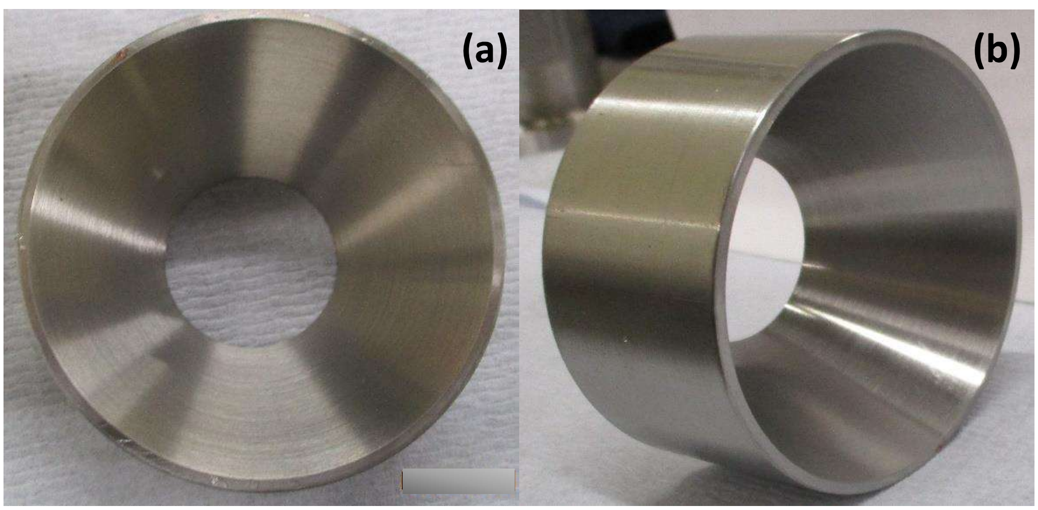


(a)



(b)

Figure 4 (a) Different parts of the downdraft gasifier (exploded view on right, 1) Bottom lid and flange, 2) bottom of gasifier below grate, 3) gasifier top part (above grate, containing annulus and throat) and parts 3 and 2 are joined by a flange, 4) Part 4 and part 5 referred to throat and annulus (inserted into part 3) and the rest is the top flange and lid, and (b) Nozzle inclination angle



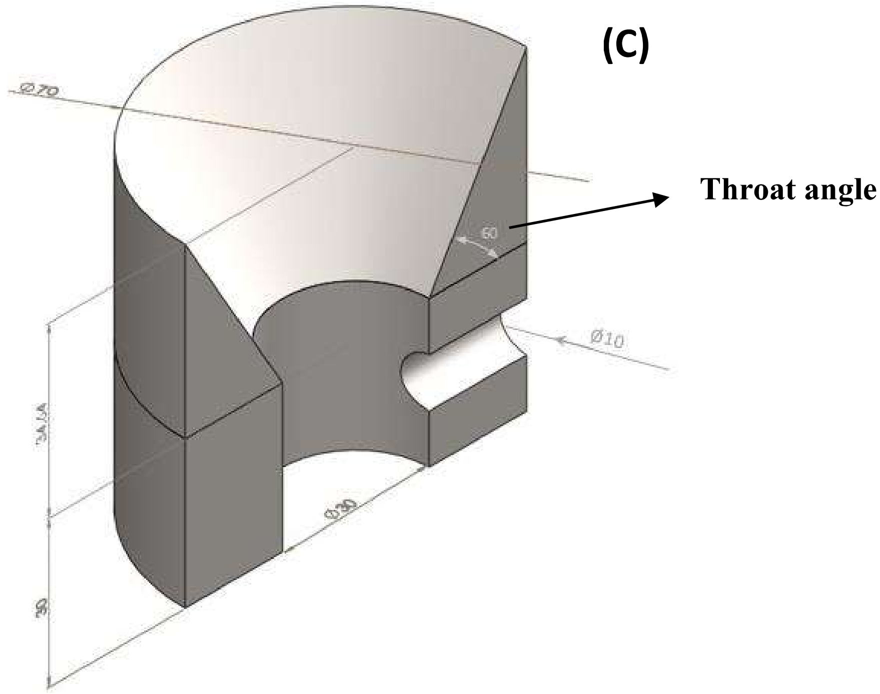


Figure 5 Front (a) and side view (b) of the throat (part 4 in figure 3) (outer diameter, 68 mm, and (c) inner hole diameter =30 mm, height =30 mm, throat angle = 60°

3.2 Flowability of new seed-propagated hybrid *Miscanthus* pellets

The flowability results of all the *Miscanthus* pellets are provided in the Table 3. A Hausner ratio between 0 and 1.11 indicates excellent flowability whereas angle of repose ranges between 0-30° [42] are considered preferred feedstock choices. The values observed for the Hausner ratio are all close to 1.0 with an angle of repose close to 30° in all cases except for the OPM53 sample, where it was 32°. Pelletizing allows higher bulk densities ranging between 700–750 kg/m^3 [43]. The pellet with the highest bulk density would be the most economically suitable for use with reduced transport cost, in this case all samples had a higher bulk density than M×g. The angle of repose and Hausner ratio measurements have shown that the *new seed*-propagated hybrid *Miscanthus* pellets (avg. 29º) have a greater flowability rating compared to wood pellets (40º) [26].

Table 3: Flowability characteristics of the different *Miscanthus* samples (6mm pellet diameter and ~15-17mm length)

Pellet	Bulk density	Hausner ratio	Pellet density	Angle of Repose
	(kg/m^3)	-	(kg/m^3)	°
M×g	547±2	0.96	986±75	26±1
OPM12	693±2	0.98	1244±34	28±3
OPM52	696±2	0.97	1267±49	28±3
OPM53	685±4	0.97	1257±53	32±1
OPM54	692±5	0.98	1259±34	29±3
Wood*	629±11	-	-	40±1

*Note: 6 mm diameter pellets, no length provided [32]

While gasifying different varieties of the *Miscanthus* pellets, the OPM52 variety broke down into powder when introduced into the top of the gasifier. The obstruction was observed in the drying section as shown in Figure 6. The powder stuck to the sidewalls of the gasifier in the drying zone and formed a bridge just above the throat which stopped the flow of the feed to the combustion and gasification zones, resulting in unsuccessful gasification. This variety was not examined further.

Figure 6 Break down of *Miscanthus* OPM52 in the gasifier

3.3 Mass balance over gasifier

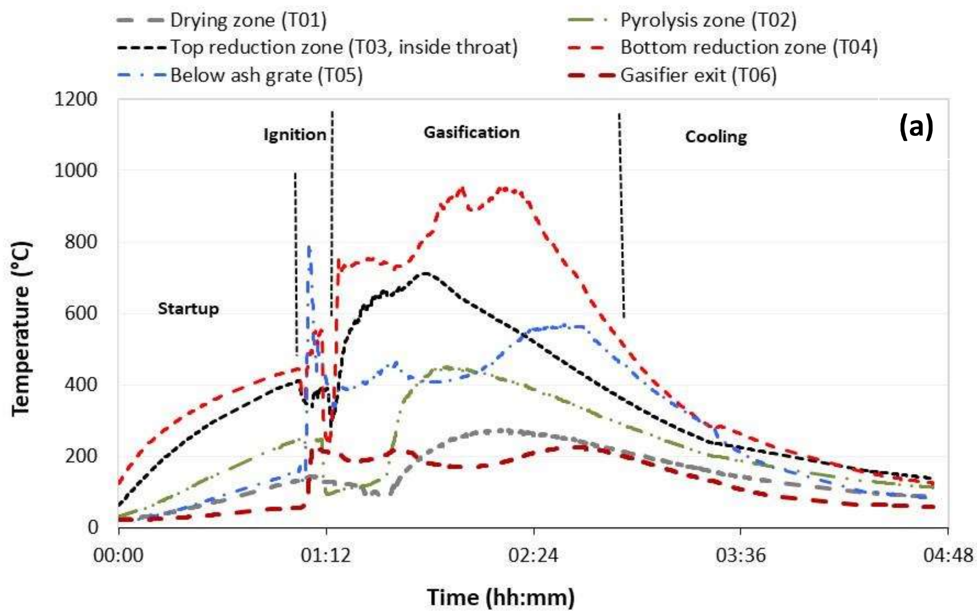
Experimental data obtained from biomass feed, air flow, ER, tar collected, ash/char left, and online measurements of product gases were evaluated for mass balance calculations in the gasifier. The mass balance was carried out at ER values of 0.25, 0.30 and 0.35 for the OPM12 sample as shown in Table 4. The leftover residue after the experiment was referred to as ash/char in the mass balance. The mass of the product gases was evaluated from the average values of gas vol% as shown in Table 5. The mass difference between the input and output might be due to any ash, char and tar deposited in the gasifier, downstream pipes and ash grate or gas leakage. It can be inferred that the mass of individual gas components increased with increasing ER ratio from 0.25-0.35 (besides some ambiguity at ER value of 0.30). The ash/char values were in close range and increasing from 0.022 kg and 0.0.020 kg at ER ratios of 0.25 and 0.35, respectively.

Table 4 Mass balance at different ER values over the experiment

ER	Input (kg)			Output (kg)									
	Feed	Air	Total	CO	H_2	CO_2	CH_4	N_2	O_2	Water	Tar	Ash /char	Total
0.25	0.7	0.87	1.57	0.119	0.003	0.179	0.022	0.700	0.031	0.066	0.064	0.022	1.210
0.30	0.7	1.04	1.74	0.079	0.001	0.171	0.001	0.801	0.068	0.065	0.062	0.021	1.269
0.35	0.7	1.21	1.91	0.154	0.004	0.240	0.028	0.945	0.013	0.064	0.060	0.020	1.564

3.4 Temperature and pressure profiles

The gasification behaviour of the hybrid *Miscanthus* OPM12 was investigated for different ER (0.25, 0.30 and 0.35) values and the temperature profiles are shown in Figures 7 (a), 8(a) and 9 (a) (respectively), whilst the corresponding product gas profiles for each ER value are shown in the respective (b) figures. The main zones consist of drying (T01), pyrolysis (T02), top reduction zone (T03, inside throat), bottom reduction zone (T04, above grate), below the grate (T05) and gasifier exit (T06), see Figure 2. Once the ignition temperature is achieved with electrical heating (in the start-up phase) above the grate and in the throat region, 100g of the *Miscanthus* pellets were fed into the gasifier and air was supplied to the top reduction zone to initiate the ignition process at 55 L/min. This ignition process lasted for 5-7 minutes and once a sufficiently high temperature (>600 ℃) was achieved, the rate was reduced to the selected ER value to start the gasification process. From Figure 7 (a), a sudden decrease is observed in T03 (from 378 to 278 ºC) and T04 (400 to 328 ºC) on the verge of the ignition point; this was due to the addition of the fresh biomass (this can also be seen in Figures 8(a) and 9(a)). After ignition, and at the start of the gasification, the temperature rises in the reduction zone with a corresponding rise in the drying and pyrolysis zones. This indicates excellent heat transfer characteristics within the small gasifier geometry. In Figure 7 (a), the temperature profile is approximately a steady state condition from 01:12-1:40 and 01:50-02:21 (hh:mm), despite batch operation. Similar conditions can be seen in Figures 8(a) and 9(a) at different times. However, the sudden increase observed in T04 (Figure 8(a) and 9 (a)) might be explained by some occasional contact between the thermocouple and glowing biomass/ash. Similar observations were also reported by Zainal *et al*. [44]. The peak temperature at the bottom of the reduction zone (T04) in the gasifier was 958, 1090 and 1092 ºC with ER values of 0.25, 0.30 and 0.35, respectively. The average temperature for gasification was in the range of 840, 846 and 866 ºC for the corresponding ER values. The average temperature range for T03 was from 550-640 ºC which is lower compared to other researchers (700-900 ºC) using pine wood as the feedstock [24]. However, this may simply be due to the position of the thermocouple in the present study relative to the reduction zone, wherein this case this thermocouple at the top of the reduction zone (T03) was fitted just inside the wall and the tip was just visible from the top of the gasifier. This arrangement was made to avoid any pellet blockage in the small throat opening (30 mm).



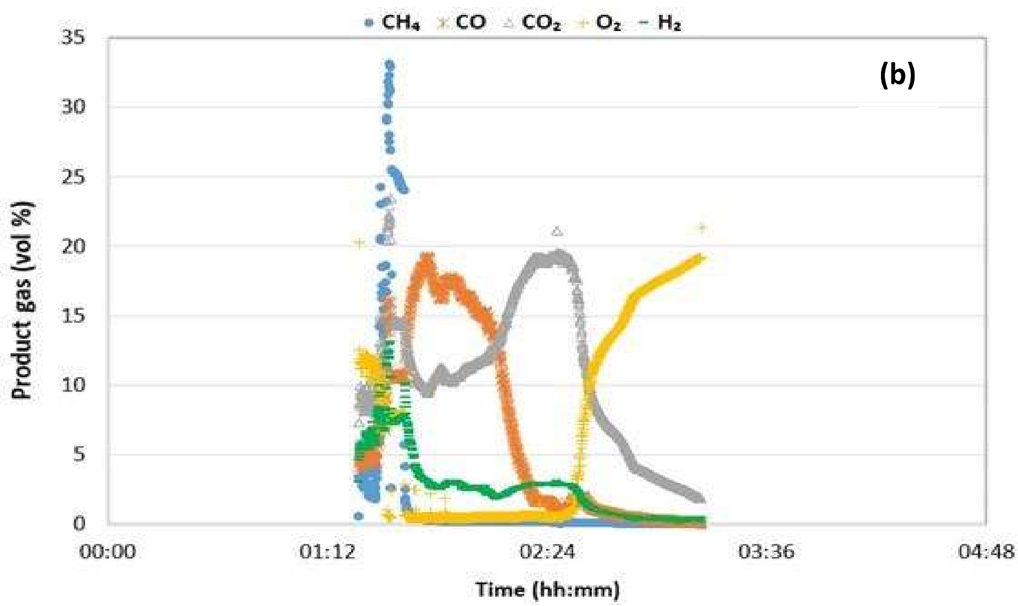


Figure 7(a) Temperature and (b) gas composition profile of hybrid *Miscanthus* (OPM12) gasification at ER=0.25

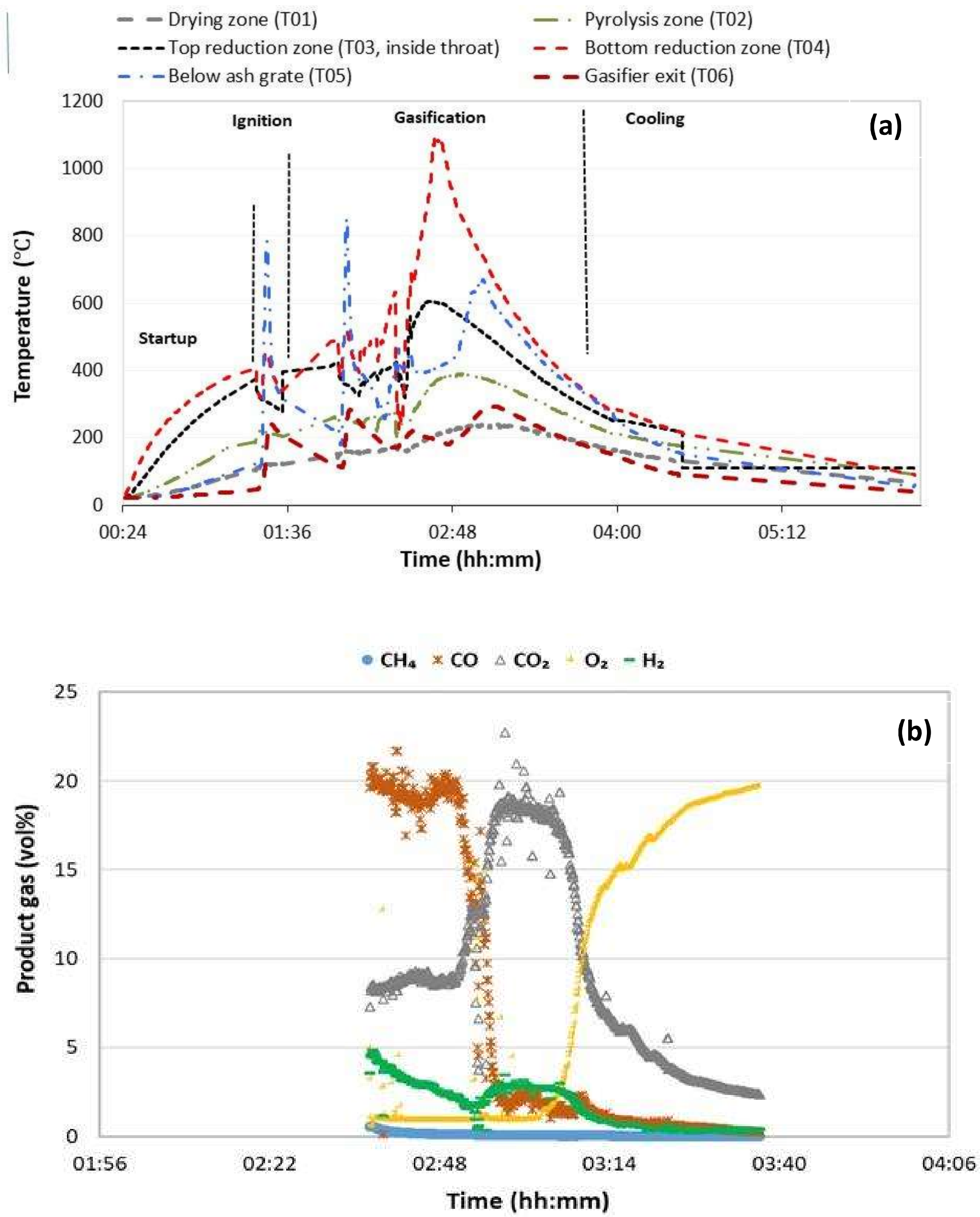


Figure 8 (a) Temperature and gas composition profiles for hybrid *Miscanthus* (OPM12) gasification at ER=0.30

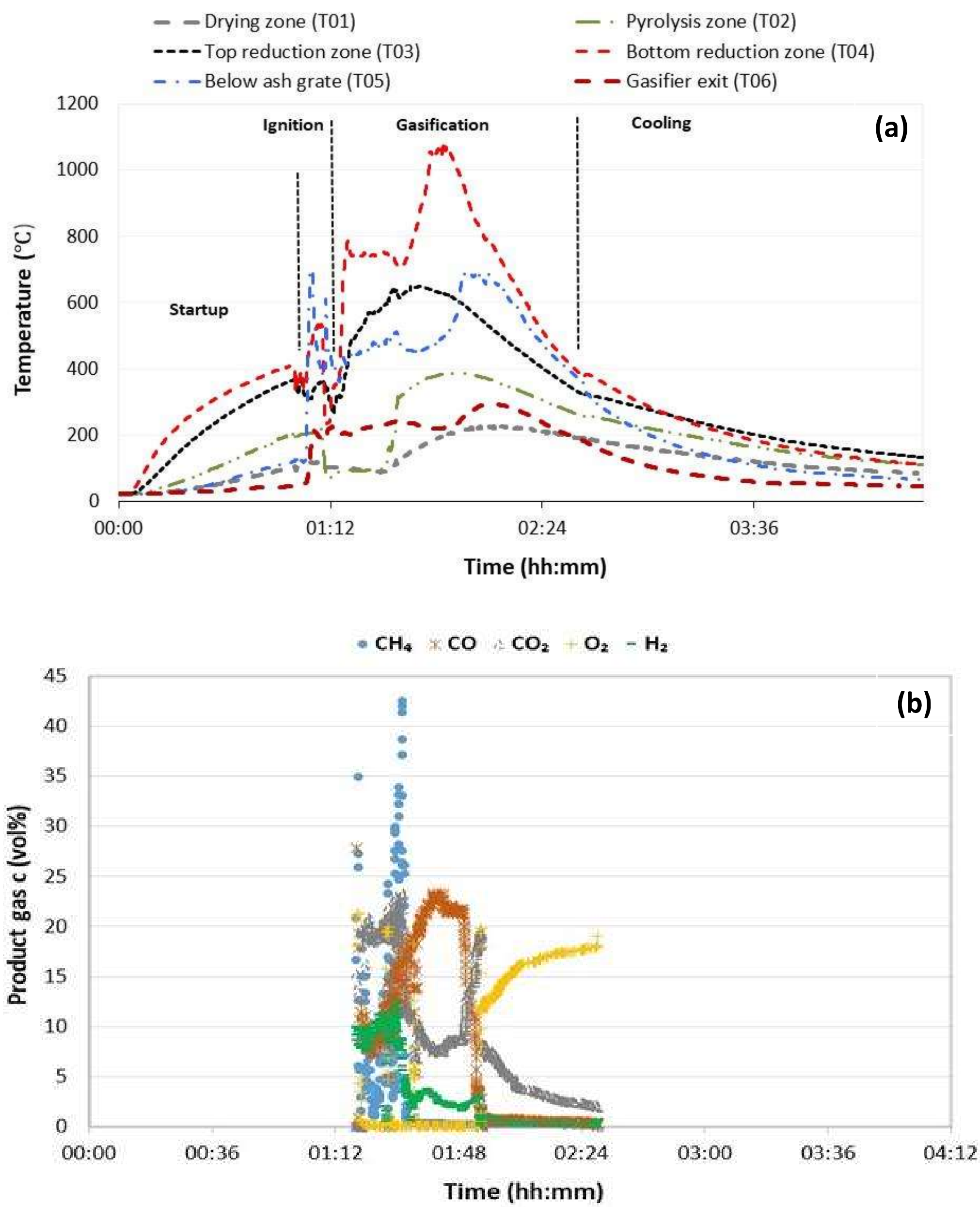


Figure 9 (a) Temperature and gas composition profiles for hybrid *Miscanthus* (OPM12) gasification at ER=0.35

3.3 Product gas composition and performance parameters

The product gas profiles at ER of 0.25, 0.30 and 0.35 are shown in Figures 7(b), 8(b) and 9(b). Some initial work on the present gasification system was previously published [23] which shows the temporal variation in the carbon conversion and cold gas efficiencies. In the present case, the results are only shown for the gasification phase of the process, outside of this range the detector was not connected to prevent damage. The initial high CH_4 concentration shows the devolatilization of the biomass pellets under gasification conditions, which gradually decreases as the biomass is converted into solid char, gas, and tar. However, the CH_4 concentration at ER=0.30 (8(b)) shows a different trend compared to ER=0.25 (7(b)) and ER=0.35 (9 (b)); which might be due to a temporary problem experienced with the CH_4 measuring sensor which was producing erroneous results. The H_2 composition starts from a high concentration, 5-12 vol%, stabilized at 2-4 vol% and reached a minimum value of < 1 vol%. The high methane concentration initially derives from the pyrolysis of the fresh feed where hemicellulose, cellulose and lignin all contribute to the methane release at low (220-330℃), medium (350-480℃) and high pyrolysis (500-650℃) temperature [45]. The low H_2 concentration in the later stages (at high temperature) is due to the exothermic nature of the water gas shift reaction [40]. The initial and final O_2 concentration refers to its standard composition in air. The fresh biomass is gradually converted into char/ash and builds up on the grate. At this stage, the Boudouard reaction (Equation 4) is the main gasification reaction and determines the final gas composition. This can be clearly seen from the CO, CO_2 and O_2 compositions between 1:12 and 2:24 hh:mm at ER=0.25, 2:48 and 3:00 hh:mm at ER=0.30 and 1:12 and 1:48 hh:mm at ER=0.35. Similar observation was made by Basu (2010) [46] which was further experimentally verified by Guangul *et al* (2012) [9] and Liu et al. (2018) [47], at temperatures exceeding 730℃.

Table 5 shows the average concentrations of the gas products over the gasification region of operation, it is seen that the gaseous concentrations of CO, CO_2, H_2, and CH_4 are lower for ER = 0.3 than for the other two ER values, and the concentrations are slightly higher for ER = 0.25. The concentrations of CO and CO_2 are mainly related through the rate of reduction in the reduction zone and its length, as discussed by Sheth *et al*. [48] for the Imbert type downdraft gasifiers in the ER range of 0.16 to 0.35. Kallis *et al*. [40] argued that the concentration of CO, CO_2 and H_2 first increases and then decreases while CH_4 decreases for an ER range of 0.20-0.30. However, it should be noted that both studies were carried out in continuous mode whereas in the present case the gasifier was operated under batch mode. Besides, gas yield, HHV_g, CC_η, and CG_η increased for ER values of 0.25 and 0.35. Again, following from the gas composition for the different ER values, these values were lowest for an ER value of 0.30, and highest for a value of 0.35. Importantly, the temperature of the reduction zone and below the grate were higher for ER = 0.35, indicating efficient cracking of tar and conversion to gas products. The pressure measured in the gasifier and hot gas filter were not too different but as would be expected increased slightly with the ER and were around atmospheric pressure (data not shown).

The results at ER=0.30 may show some ambiguity based on a very low CH_4 concentration (0.09 vol%) in the product gas which further contributes to a lower gas yield, HHV_g and CG_η. Similarly, the average H_2 content (2.20 vol%) at ER of 0.30 is almost half of the value observed at 0.25 (4.23 vol%) and 0.35 (5.06 vol%). Based on the results presented, the optimum value of ER is found to be 0.35 for better gas composition and performance parameters. However, future work needs to be carried out to further identify optimal performance parameters.

Table 5 Average temperature, pressure, gas composition and performance parameters for OPM12

Biomass mass	[kg]	0.70	1.35	1.35
ER	[-]	0.25	0.30	0.35
Air flowrate	[L min^{-1}]	12.00	14.33	16.67
Gasifier pressure	bar	0.956	0.995	1.013

Temperature	[ºC]			
Drying zone (T01)		196	218	165
Pyrolysis zone (T02)		349	364	309
Top reduction zone (T03)		639	557	606
Bottom reduction zone (T04)		842	846	866
Below grate (T05)		438	500	531
Gasifier exit (T06)		188	226	240
Average gas composition [vol %]				
CO		12.82	7.83	14.00
CO_2		12.16	10.72	13.78
H_2		4.23	2.20	5.06
CH_4		4.14	0.09	4.41
O_2		2.93	5.87	1.00
Gas yield	($m^3\ kg_{biomass}^{-1}$)	0.42	0.34	1.32
HHV	[MJ m^{-3}]	3.81	1.25	4.17
Cold gas efficiency (CG_η)	[%]	25.36	9.40	32.31
Carbon conversion efficiency (CC_η)	[%]	58.06	40.60	74.00

A comparison of these experimental results of gasifiying the hybrid *Miscanthus* with the results of Kallis *et al*. [40], utilizing two different type of *Miscanthus* pellets in a pilot scale downdraft gasifier (throat-less), at an ER ratio of 0.27-0.28, can be seen in Table 6. The comparative study shows improved system efficiencies even at low ER (0.25) in the present study. A good heating value is produced when compared with the literature for almost similar ER values along with a higher conversion efficiency. From Table 6, it can be seen that the performance of the new seed-propagated hybrid *Miscanthus* pellets compare well in terms of gasification properties with conventional pellets in the literature. This demonstrates satisfactory operation of the gasifier as a standard, laboratory facility to allow comparison of different feedstocks and demonstrates the suitability of OPM12 as a suitable *Miscanthus* variety.

Table 6 Comparison of gasification experimental batch results against the literature

Biomass type	ER	HHV_g (MJ m^{-3})	Cold gas efficiency (%)	Carbon conversion efficiency (%)	Reference
Hybrid *Miscanthus* *OPM12* pellets	0.25	3.81	25.36	58.06	*Present study*
EON *Miscanthus* pellets (Type 1)	0.28	4.0	30.0	47.0	*Kallis et al.* [40]
Simple *Miscanthus* pellets (Type 2)	0.27	2.8	18.8	31.9	

Conclusions

The design and development of a laboratory scale downdraft gasifier was carried out and gasification experiments were conducted using a novel seed-propagated hybrid *Miscanthus* OPM12. Initially, two important gasifier dimensions, throat diameter and the diameter of the gasifier, were evaluated through hearth load and gasification rate, comparing the design using two reaction schemes with comparative results. A suite of instrumentation and control systems was successfully developed utilizing the Arduino platform to measure temperature, pressure, and mass flow at strategic points around the system. The effect of ER in the range of 0.25-0.35 on gas yield, gas heating values, cold gas efficiency and carbon conversion efficiency were studied for a new seed-propagated hybrid Miscanthus (*Miscanthus* OPM12). Experimental results were further compared to data from the literature for conventional *Miscanthus* pellets, and it was found that the new variety (*Miscanthus* OPM12) under these test conditions performed comparably. The gasifier and instrumentation have been found easy to construct and operate. The instrumentation of course can be used on different scaled downdraft gasifiers or different gasifier designs. Standardizing such equipment allows direct comparisons between different feedstocks globally, addressing issues of scalability and allow downstream testing of novel tar detection systems, gas cleanup methods or catalyst performance.

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References

[1] Laohalidanond K, Kerdsuwan S. Green energy recovery from waste in thailand: Current situation and perspectives. International Journal of Energy for a Clean Environment. 2021;22:103-22, http://dx.doi.org/10.1615/InterJEnerCleanEnv.2021037107.

[2] Molino A, Chianese S, Musmarra D. Biomass gasification technology: The state of the art overview. Journal of Energy Chemistry. 2016;25:10-25, https://doi.org/10.1016/j.jechem.2015.11.005.

[3] Susastriawan AAP, Saptoadi H, Purnomo. Small-scale downdraft gasifiers for biomass gasification: A review. Renewable and Sustainable Energy Reviews. 2017;76:989-1003, http://dx.doi.org/10.16/j.rser.2017.03.112.

[4] Chandolias K, Richards T, Taherzadeh MJ. Chapter 5 - Combined gasification-fermentation process in waste biorefinery. In: Bhaskar T, Pandey A, Mohan SV, Lee D-J, Khanal SK, editors. Waste Biorefinery: Elsevier; 2018. p. 157-200.

[5] Bermudez JM, Fidalgo B. 15 - Production of bio-syngas and bio-hydrogen via gasification. In: Luque R, Lin CSK, Wilson K, Clark J, editors. Handbook of Biofuels Production (Second Edition): Woodhead Publishing; 2016. p. 431-94.

[6] Sikarwar VS, Ji G, Zhao M, Wang Y. Equilibrium modeling of sorption-enhanced cogasification of sewage sludge and wood for hydrogen-rich gas production with in situ carbon dioxide capture. Industrial & Engineering Chemistry Research. 2017;56:5993-6001.

[7] Reed T, Das A. Handbook of Biomass Downdraft Gasifier Engine Systems. Springfield, United State Solar Energy Research Institute, U.S. Department of Commerce; SERIISP-271-3022, 1988.

[8] Bocci E, Sisinni M, Moneti M, Vecchione L, Di Carlo A, Villarini M. State of art of small scale biomass gasification power systems: A review of the different typologies. Energy Procedia. 2014;45:247-56, https://doi.org/10.1016/j.egypro.2014.01.027.

[9] Guangul FM, Sulaiman SA, Ramli A. Gasifier selection, design and gasification of oil palm fronds with preheated and unheated gasifying air. Bioresource Technology. 2012;126:224-32.

[10] Ingle NA, Lakade SS. Design and development of downdraft gasifier to generate producer gas. Energy Procedia. 2016;90:423-31.

[11] Pathak BS, Patel SR, Bhave AG, Bhoi PR, Sharma AM, Shah NP. Performance evaluation of an agricultural residue-based modular throat-type down-draft gasifier for thermal application. Biomass and Bioenergy. 2008;32:72-7.

[12] Shrinivasa U, Mukunda HS. Wood gas generators for small power (~ 5 hp) requirements. Sadhana. 1984;7:137-54.

[13] Dasappa S, Reddy V, Mukunda HS, Shrinivasa U. Experience with gasifiers for 3.7-kW engines. Ambio. 1985;14:275-9.

[14] Sutar KB, Kohli S, Ravi MR. Design, development and testing of small downdraft gasifiers for domestic cookstoves. Energy. 2017;124:447-60.

[15] Singh A, Yadav VK, Shrivastava D, Singh MK, Maurya S, Vibhanshu V, et al. Estimation of performance parameter of top-lit up-draft cookstove using locally available wood feedstock. International Journal of Energy for a Clean Environment. 2021;22:129-46, http://dx.doi.org/10.1615/InterJEnerCleanEnv.2021036706.

[16] Felten D, Fröba N, Fries J, Emmerling C. Energy balances and greenhouse gas-mitigation potentials of bioenergy cropping systems (Miscanthus, rapeseed, and maize) based on farming conditions in Western Germany. Renewable Energy. 2013;55:160-74.

[17] Greef JM, Deuter M. Syntaxonomy of Miscanthus x giganteus Greef et Deu. Angewandte Botanik. 1993;67:87-90.

[18] Clifton-Brown J, Hastings A, Mos M, McCalmont JP, Ashman C, Awty-Carroll D, et al. Progress in upscaling Miscanthus biomass production for the European bio-economy with seed-based hybrids. GCB Bioenergy. 2017;9:6-17.

[19] Kalinina O, Nunn C, Sanderson R, Hastings AFS, van der Weijde T, Özgüven M, et al. Extending miscanthus cultivation with novel germplasm at six contrasting sites. Frontiers in Plant Science. 2017;8.

[20] Kamble P, Khan Z, Capper S, Sharp J, Watson I. Improving downdraft gasifier stability by robust instrumentation and control systems. Energy Procedia. 2017;142:2214-7.

[21] Reguera P, García D, Domínguez M, Prada MA, Alonso S. A low-cost open source hardware in control education. Case study: Arduino-feedback ms-150. IFAC-PapersOnLine. 2015;48:117-22.

[22] Khan Z, Yusup S, Ahmad MM, Inayat A, Naqvi M, Sheikh R, et al. Integrated catalytic adsorption steam gasification in a bubbling fluidized bed for enhanced H2 production: perspective of design and pilot plant experiences. Biofuels, Bioproducts and Biorefining. 2018;0.

[23] Kamble P, Khan Z, Gillespie M, Farooq M, McCalmont J, Donnison I, et al. Biomass gasification of hybrid seed Miscanthus in Glasgow's downdraft gasifier testbed system. Energy Procedia. 2019;158:1174-81.

[24] Lv P, Yuan Z, Ma L, Wu C, Chen Y, Zhu J. Hydrogen-rich gas production from biomass air and oxygen/steam gasification in a downdraft gasifier. Renewable Energy. 2007;32:2173-85.

[25] Guo F, Dong Y, Dong L, Guo C. Effect of design and operating parameters on the gasification process of biomass in a downdraft fixed bed: An experimental study. International Journal of Hydrogen Energy. 2014;39:5625-33.

[26] Wu MR, Schott DL, Lodewijks G. Physical properties of solid biomass. Biomass and Bioenergy. 2011;35:2093-105.

[27] Bunchan S, Poowadin T, Trairatanasirichai K. A study of throat size effect on downdraft biomass gasifier efficiency. Energy Procedia. 2017;138:745-50.

[28] Prasertcharoensuk P, Hernandez DA, Bull SJ, Phan AN. Optimisation of a throat downdraft gasifier for hydrogen production. Biomass and Bioenergy. 2018;116:216-26.

[29] Kaushal P, Abedi J, Mahinpey N. A comprehensive mathematical model for biomass gasification in a bubbling fluidized bed reactor. Fuel. 2010;89:3650-61.

[30] Basu P. Chapter 7 - Gasification theory. In: Basu P, editor. Biomass gasification, pyrolysis and torrefaction (Second Edition). Boston: Academic Press; 2013. p. 199-248.

[31] T. B. Reed RW, S. Ellis, A. Das, S. Deutch. Superficial velocity - the key to downdraft gasification. 4th Biomass Conference of the Americas, 28 August,. Oakland, CA, USA 1999.

[32] Kishore VVN. Renewable Energy Engineering and Technology: A Knowledge Compendium. New Delhi, India, Energy and Resources Institute; 2008.

[33] S.SivaKumar, N.Ranjithkumar, S.Ragunathan. Design and development of down draft wood gasifier. International Journal of Mechanical 2013;2:1-10.

[34] S.J. Ojolo JIO. Design and development of a laboratory scale biomass gasifier. Journal of Energy and Power Engineering. 2010;4:16-23.

[35] Sivakumar S, Pitchandi, K., , Natarajan E. Design and analysis of downdraft biomass gasifier using computational fluid dynamics. International Congress on Computational Mechanics and Simulation (ICCMS 06), 8-10 December. Guwahati, India 2006.

[36] Kaupp A, Goss JR. Technical and economical problems in the gasification of rice hulls. Physical and chemical properties. Energy in Agriculture. 1981;1:201-34.

[37] Tiangco VM, Jenkins BM, Goss JR. Optimum specific gasification rate for static bed rice hull gasifiers. Biomass and Bioenergy. 1996;11:51-62.

[38] Radmanesh R, Chaouki J, Guy C. Biomass gasification in a bubbling fluidized bed reactor: Experiments and modeling. AIChE Journal. 2006;52:4258-72.

[39] Shi H, Si W, Li X. The concept, design and performance of a novel rotary kiln type air-staged biomass gasifier. Energies. 2016;9:67.

[40] Kallis KX, Pellegrini Susini GA, Oakey JE. A comparison between Miscanthus and bioethanol waste pellets and their performance in a downdraft gasifier. Applied Energy. 2013;101:333-40.

[41] Materials A. Stainless steel - Properties and applications of grades 310/310s stainless steel NSW, Australia: Austral Wright Metals; 2008 (Access date: Feburary 14, 2022).

[42] Miao Z, Grift TE, Hansen AC, Ting KC. Flow performance of ground biomass in a commercial auger. Powder Technology. 2014;267:354-61.

[43] Tumuluru JS. Effect of pellet die diameter on density and durability of pellets made from high moisture woody and herbaceous biomass. Carbon Resources Conversion. 2018;1:44-54.

[44] Zainal ZA, Rifau A, Quadir GA, Seetharamu KN. Experimental investigation of a downdraft biomass gasifier. Biomass and Bioenergy. 2002;23:283-9.

[45] Yang H, Yan R, Chen H, Lee DH, Zheng C. Characteristics of hemicellulose, cellulose and lignin pyrolysis. Fuel. 2007;86:1781-8.

[46] Basu P. Biomass gasification and pyrolysis: Practical design and theroy: Academic Press; 2010.

[47] Liu L, Huang Y, Cao J, Liu C, Dong L, Xu L, et al. Experimental study of biomass gasification with oxygen-enriched air in fluidized bed gasifier. Science of The Total Environment. 2018;626:423-33.

[48] Sheth PN, Babu BV. Experimental studies on producer gas generation from wood waste in a downdraft biomass gasifier. Bioresource Technology. 2009;100:3127-33.