Optimal Design of Gasifier Reactor for Crop Residues Gasification Using Integrated MCDM Techniques/QFD Approach*

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Abstract

Gasification technology has a critical role to play in the quest to provide off and on-grid renewable energy solutions for rural agricultural communities. Optimal gasifier design is essential for sustainable energy generation and operation of gasifier systems. The aim of this study is therefore to design an optimal gasifier reactor for the gasification of crop residues using Integrated Multicriterial Decision Making (MCDM) Techniques and Quality Function Deployment (QFD) methodological approach. The MCDM/QFD framework consists of user requirement, engineering parameters and seven gasifier types. The engineering parameters were categorised under five sections and the best gasifier type under each category was determined using Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The design characteristics of the best ranked gasifier type under each category was incorporated into a stratified downdraft gasifier reactor type. The characteristic of five crop residues and consideration of a 10-kW engine system for electricity generation was used to size and designed the gasifier reactor. The study revealed that updraft gasifier is the optimal gasifier that is efficient and can handle wide range of feedstock characteristics. Similarly, stratified downdraft and circulating fluidized bed gasifier are the optimal in terms gasifier operating conditions and good syngas quality respectively. A 45-kW semi-batch stratified Downdraft (SD) Gasifier with internal diameter and height of 0.36 m and 1.7 m respectively were designed based on average fuel consumption of 23 kg/hr and an airflow rate of 26.31 m^3/hr. The optimal gasifier consists of a screw auger system, an extended ash collection bunker, and a gas recirculation combustion unit.

Keywords: QFD, MCDM, Stratified, Downdraft, Gasifier, Crop Residues

1 Introduction

Worldwide, about 700 million people have no access to electricity mostly in Asia and Africa. Sub-Saharan African countries share of the global population without access to electricity is about 77% (Anon., 2022a). Renewable energy is expected to play a significant role in meeting these deficits by providing an environmentally benign energy source. As of 2020, modern renewable energy accounted for an estimated 12.6% of the world Total Final Energy Consumption (TFEC), nearly one percentage point higher than in 2019 (Anon., 2022b). Among renewable energy, bioenergy plays a critical role in Ghana's energy sector and in many other sub-Saharan African countries mainly for cooking. Bioenergy in the form firewood and charcoal accounted for approximately 34% of the total energy supply in 2021 in Ghana (Anon., 2022c). The current use of biomass for bioenergy generation in the form of firewood and charcoal is unsustainable and contributes to deforestation causing climate change at local and global levels (Osei *et al*., 2021). Due to agricultural activities in Ghana, significant quantities of crop residues (e.g. rice husk, maize stalk,cocoa pod husk etc.) are generated annually which in most cases are openly burnt generating greenhouse gases (Kemausuor *et al*., 2014). However, these crop residues can be used to sustainably generate bioenergy for heat and electricity generation using different converting technologies.

Among the conversion technologies, gasification is one of the efficient and best for the reuse of crop residues as it provides an opportunity for small-scale applications for both electricity and heat generation with lower Greenhouse gas emissions (Akolgo *et al*., 2019; Pereira *et al*., 2012). Gasification is the thermal decomposition of biomass at higher temperatures between 600 ºC to 1200 ºC and in a less oxygen-restricted environment which leads to the formation of a synthesis gas (syngas) with the constituent being hydrogen (H_2), Carbon monoxide (CO), Carbon dioxide (CO_2) and Methane (CH_4), as well as light (propane) and heavier hydrocarbons (tars). The gasification process occurs in four stages (drying, pyrolysis, reduction and combustion) and the order in which they occur depends on the gasifier reactor type (Patra and Sheth, 2015). Syngas can be used directly for heat applications such as cooking, drying crops, etc. When cleaned to remove tar and carbon dioxide, it can be used in combustion engines, micro-turbines, fuel cells or gas turbines for electricity generation. The quantity, quality, and composition of the syngas are dependent mostly on the gasifier type (Abubakar *et al*., 2019), gasifying medium (air, oxygen, steam or a combination) (Banerjee *et al*., 2015) operating condition (e.g., pressure, temperature, Equivalence ratio etc) (Atnaw, 2017) and feedstock characteristics (proximate, ultimate and heating values) (Banerjee *et al*., 2015). There are three main configurations of gasifiers; "fixed bed", "fluidized bed" or

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"entrained flow" depending on the interactions between the feedstock and gasifying agent (Basu, 2018).

Even though the gasification technology is quite mature and reliable, it is not vastly deployed in Ghana with few installations across the country due to some challenges (Akolgo *et al*., 2019; Osei *et al*., 2021). Installed gasification systems in Ghana are faced with some challenges resulting in unsustainable operations. Some have broken down after a few operational hours (Owen and Ripken, 2017). Inefficient reactor design, ash handling, gas cleaning, tar content minimization, moisture content reduction and lack of tailor-made technology to suite locally available residues are reported technical challenges (Osei *et al*., 2021; Akolgo *et al*., 2019; Owen and Ripken, 2017; Anon.,2016; Kontor, 2013). Optimal gasifier design and operational conditions can be used to tackle these problems.

Gasifier design is essential for optimal syngas generation. Design parameters controls the performance of a gasifier. These factors include the reactor type. This controls the gasification performance since each gasifier type has special design structures that improve heat transfer, reduce tar content, or improve gas quality. Fluidised bed gasifiers are excellent in terms of heat transfer while fixed bed gasifiers are well known for their ease of operation and simplicity (Ahmad *et al*., 2016). Another design factor is the cross-sectional area of the reactor where the fuel is gasified. The gas output of the gasifier increases with the increasing cross-sectional area. For uniform gasification, a circular cross-sectional area is preferable to a square or rectangular cross-section (Abubakar *et al*., 2019). Moreover, the reactor height determines the retention time and quantity of feedstock that can be gasified in one cycle. Fan airflow rate and pressure and the quantity of air required for gasification also affects the gasifier design. The fan size and position affect the gasification as the fan should be able to overcome the pressure exerted by the biomass and char. The fan size and position differ with different gasifier types and gasifier sizes (Abubakar *et al*., 2019). Insulation of the reactor also affects the reactor design. The reactor insulation retains heat within the reactor and protects personnel operating the reactor.

A number of approaches have been used to optimise gasifier design and to determine optimal operating conditions. Experimental approach and the use of equilibrium and kinetic mathematical modelling or a combination have been used (Commeh *et al*., 2019; Chaurasia, 2016; Salem and Paul, 2018). In kinetic modelling, both temperature and gas composition inside the gasifier can be estimated and optimised concerning the gasifier geometry. Kinetic models are comprehensive and more accurate but need robust computers to perform the required calculations (Chaurasia, 2016; Gagliano *et al*., 2016). The thermodynamic equilibrium model even though is less calculation intensive does not take into consideration the geometry of the reactor (Moretti *et al*., 2022; La Villetta *et al*., 2017). Experimental procedures provide a more practical and realistic approach but it is limited in the number of experiments that can be performed. These approaches to optimising gasifier design in most cases do not take into consideration most of the existing technical, economic and operational challenges with the installed gasifier systems, particularly in the context of Ghana.

The existing gasifier designs in Ghana are not tailored to the unique technical challenges which include: inefficient reactor design, the inability of reactors to use multiple feedstocks, ash handling, gas cleaning, tar content minimization, moisture content reduction and lack of tailor-made technology to suit locally available crop residues. Existing methods for the design of gasifier reactors are unable to holistically take into consideration all existing technical/economic challenges in the quest to design a reactor to solve these challenges. Therefore, there is a need to adopt a design approach that takes into consideration the existing challenges of the installed gasifier systems. Osei *et al.* (2022) developed an integrated Multicriteria Decision Making techniques (MCDM)/Quality Function Deployment (QFD) methodological approach to select optimal gasifier type for crop residue gasification in Ghana taken into consideration user requirement and gasifier engineering parameters. The MCDM techniques used are Analytical Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The study established that stratified downdraft gasifier reactor is the best gasifier type for crop residue gasification in Ghana. The Integration of AHP allows the combination of the end user of the technology point of view (using QFD) and expert opinion (using AHP). The integration of the QFD and TOPSIS allows the optimal evaluation of the best technology types by maximising (desired engineering parameters) and minimizing (undesired engineering parameters) based on the relative importance of each engineering parameter concerning the end user's requirement.

A comprehensive methodological approach taking into account concerns of end users and optimal technical parameters from experimental/mathematical modelling methods and harnessing the advantages in the various gasifier types can present an optimal gasifier design that can fit the Ghanaian situation. The aim of this study is, therefore, to design an optimal gasifier for crop residue gasification in Ghana using MCDM/QFD methodological approach. No known study has employed QFD in the optimal design of gasifier reactors particularly the integration of MCDM and QFD in the design of a gasifier reactor.

The outcome of the study is expected to contribute significantly to the sustainable utilisation of crop residues for gasification which will contribute to the governments of Ghana's efforts to develop bioenergy conversion technologies as part of the renewable energy Masterplan (Anon., 2019). The findings of this study would therefore be useful to technologists, bioenergy entrepreneurs, governments, energy planners, policy makers, utilities and international organizations that are engaged in developing bioenergy, particularly gasification systems for rural communities.

2 Resources and Methods Used

Fig. 1 presents the general methodological approach used in this study. This consist of the various sections of the Integrated QFD/MCDM framework and how it is linked to the optimal design of the gasifier reactor. The Integrated QFD/MCDM framework developed by Osei *et al*. (2022) for optimal evaluation of gasifier reactor type for crop residue gasification in Ghana was used. Fig. 2 presents the composition of the QFD/MCDM framework. The first stage is the identification of critical technical/economic user requirement for the design of optimal gasifier for crop residues. These criteria are then weighted using AHP. The weighted criteria together with the technical (Engineering) parameters for the design of gasifiers and various types of gasifier reactors were then used to develop the QFD. The detailed description of the QFD/MCDM framework is described in details by Osei *et al.* (2022).

Stratified downdraft gasifier has been reported as the optimal gasifier type for crop residues selected as the best gasifier reactor type for crop residue gasification in Ghana (osei *et al*., 2022). This therefore served as the base case design. Five gasifier alternative designs were considered in this study. These include: throated downdraft gasifier (TD); stratified downdraft gasifier (SD), updraft gasifier (UP), cross draft gasifier (CD), bubbling fluidized bed gasifier (BFG), circulating fluidized bed gasifier (CFG) and entrained flow gasifiers (EFG) (Sansaniwal *et al*., 2017; Guangul *et al*., 2012). As shown in Fig. 1, the gasifier reactor types were further ranked based on five sub-categories of engineering parameters; Sub-category 1 (fuel characteristics (FC)) consists of moisture content, particle size and ash content; Sub-category 2 (Gasifier efficiency(EF)) consists of gasifier thermal, cold gas and carbon conversion efficiency; subcategory 3 (operating conditions(OP)) consists of temperature, pressure and equivalence ratio; sub-category 4 (syngas quality(SQ)) consisting of tar, syngas H_2/CO ratio and syngas heating value and lastly sub-category 5 consisting of (gasifier capacity). In each sub-category, the optimal gasifier reactor type was determined using TOPSIS. The baseline gasifier reactor type (stratified downdraft gasifier (GC)) was modified based on the outcomes of the rankings of the gasifier reactor type under the various sub categories.

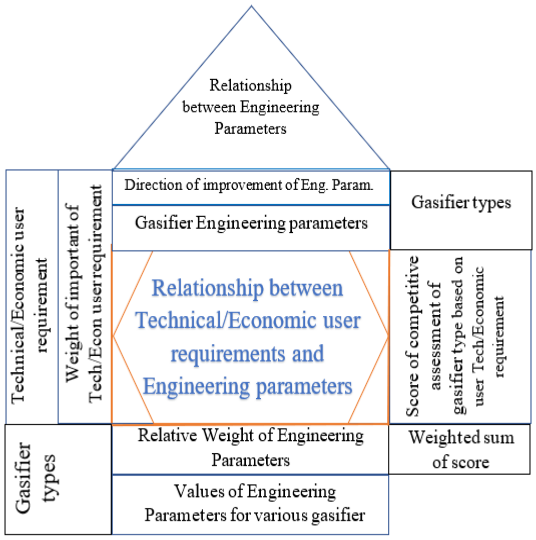

Fig. 2 Schematic of QFD/MCDM Framework

2.1 Rankings of Gasifier Reactor Types Under Engineering sub-category Using TOPSIS

The various gasifier reactor types and the values of the engineering parameters were used to form the decision matrix for the TOPSIS (see Table 1 for the alternative, criteria and the values of the decision matrix). The six gasifier types and the thirteen engineering parameters served as the decision alternatives and criteria respectively.

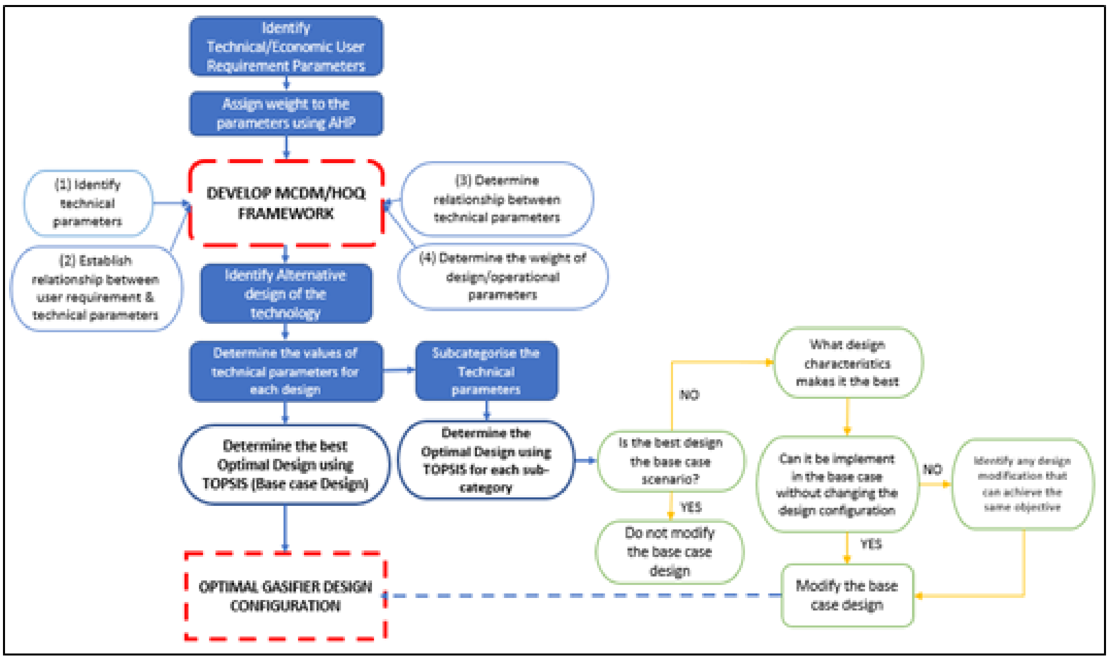

Fig. 1 MCDM/QFD Model for Design of Optimal Gasifier

Table 1 Alternatives and Criteria for the decision matrix

	Tar produced (g/Nm^3 of syngas	Acceptable as content (%)	Gasifier thermal efficiency (rank)*	Minimum Capacity (kW)	Operating temperature (^{o}C)	Operating Pressure (bar)	Syngas H_2/CO ratio	Syngas heating value (MJ/Nm^3)	Cold Gas efficiency (rank)*	Carbon conversion rate (%)	Equivalence ratio	Acceptable operating moisture content (%)	Acceptable range of particle size (mm)
Throated Downdraft Gasifier	3.00	5.00	6.00	9.00	1500.00	1.00	0.76	3.91	3.00	96.00	0.30	25.00	100.00
Stratified Downdraft Gasifier	1.34	5.00	6.00	9.00	1500.00	1.00	0.70	4.41	3.00	96.00	0.40	25.00	100.00
Updraft Gasifier	150.00	25.00	9.00	2.00	900.00	1.00	0.60	4.73	9.00	99.80	0.32	50.00	100.00
Crossdraft Gasifier	0.10	1.00	6.00	10.00	1500.00	1.00	0.62	4.50	1.00	85.00	0.35	20.00	20.00
Bubbling Fluidized bed gasifier	12.00	40.00	3.00	1000.00	900.00	10.00	0.92	4.26	3.00	91.00	0.35	30.00	10.00
Circulating Fluidized bed gasifier	8.00	40.00	6.00	200.00	900.00	1.00	0.94	4.60	6.00	88.96	0.30	30.00	6.00
Entrained Flow Gasifiers	0.00	20.00	1.00	1000.00	1990.00	20.00	0.65	4.36	3.00	99.50	0.25	15.00	0.15
Weights of Engineering Parameters	0.0790	0.075	0.0861	0.085	0.0981	0.0575	0.035	0.0577	0.051	0.0835	0.0935	0.1018	0.0959
Objective of criteria	Minimise	Mazimise	Mazimise	Minimise	Mazimise	Minimise	Mazimise	Mazimise	Mazimise	Mazimise	Mazimise	Mazimise	Mazimise

*The gasifier types were ranked as 9, 6, 3, and 1 with 9 and 1 representing strongest and weakest value respectively

Source: (Osei *et al*., 2022)

Table 1 also presents the relative weight of importance of each of the engineering parameters. The values were determined based on the output of the QFD/MCDM framework as developed and reported by Osei *et al.* (2022). The following four steps were used to rank the various alternatives (gasifier types) under the various five sub-categories of the engineering parameters:

i. **Step 1:** The decision matrix was normalize using Equation 1a.

$$r_{ij} = X_{ij} \Big/ \sqrt{\sum_{j=1}^{n} X_{ij}^{2}} \quad (1a)$$

$$where\ i = 1,2,\ldots.,m;j = 1,2,\ldots,n$$

ii. **Step 2:** Provide weight to the matrix using Equation 1b.

$$V_{ij} = w_j \times r_{ij} \quad (1b)$$

$$where\ i = 1,2,\ldots.,m;j = 1,2,\ldots,n$$

$w_j = is\ the\ weight\ of\ the\ criteria\ as\ determined\ from\ the\ QFD$

iii. **Step 3: T**he best Ideal Solution and nadir solution were then defined as follows:

$$A^* = \{V_1^*, V_2^*, \ldots\ldots, V_n^*\} = \{(max_j v_{ij} | i \in I'), (min_j v_{ij} | i \in I'')\}$$

$$i = 1,2,\ldots\ldots,m; j = 1,2,\ldots,n.$$

$$A^- = \{V_1^-, V_2^-, \ldots\ldots, V_n^-\} = \{(min_j v_{ij} | i \in I'), (max_j v_{ij} | i \in I'')\}$$

$$i = 1,2,\ldots\ldots,m; j = 1,2,\ldots,n.$$

where I' is related to benefit attributes and I'' is related to cost or non-beneficial attributes

iv. **Step 4:** achieve the remoteness of all choices from A^+ and A^- were then achieved using Equations 1c and 1d.

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2} \quad i = 1,2,\ldots\ldots,m \quad (1c)$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \quad i = 1,2,\ldots.,m \quad (1d)$$

v. **Step 5**: Equation 1e was used to determine relative closeness to the perfect solution.

$$CC_i^* = D_i^- \Big/ D_i^- + D_i^+ \quad (1e)$$

$$i = 1,2,\ldots.,m$$

vi. **Step 6:** The alternatives were then prioritised using CC_i^*. The larger CC_i^* indicates better accomplishment of options.

2.3 Method for the Design of the Optimal Gasifier Reactor

As indicated earlier, stratified downdraft gasifier served as the base case gasifier type on which the optimal gasifier was developed. The best characteristics of the optimal gasifier reactor type under each sub-categories were incorporated in the base case design based on the design types as presented in Fig. 3. The average characteristics of multiple crop residues feedstocks (rice husk & stalk, maize stalk, husk and cobs, cocoa pod husk) were used as the reference feedstock for sizing the reactor. In this study, a 10-kW engine gasifier system for electricity generation was considered. Fuel Consumption Rate (FCR) (kg/hr) and Air flow rate (AFR) (m^3/hr) were determined for the various feedstock using Equations 2a and 2b respectively.

$$FCR = \frac{CSP \times 3600}{(CGE/100\%) \times 1000 \times CV_{feedstock}} \quad (2a)$$

where:

$CGE = Cold\ Gas\ Efficiency$

$CV_{feedstock} = Calorific\ values\ of\ feedstocks$

The values of CGE and $CV_{feedstock}$ for the various feedstocks as presented by Osei (2023) were used.

$$Gasifier\ capacity\ (GC)(kW) = \frac{10\ (kW)}{EF_E/100\%}$$

EFE is the efficiency of the internal combustion engine, a value of 20% was used (Anon., 2021b)

$$AFR\ (m^3/h) = \frac{FCR\ (kg/h) \times n_{air}}{1.223\ (kg/m^3)} \quad (2b)$$

where: n_{air} is the average stoichiometric amount of air required for the various feedstock as determined by Osei (2023).

2.3.1 Reactor Cross-sectional area

This parameter represents the cross-sectional area of the reactor. It was determined using Equation 3.

$$Reactor\ cross\ sectional\ area\ (m^2) = \frac{FCR}{SGR} \quad (3)$$

where:

Fuel Consumtion rate (FCR) $= 23$ (kg/hr)
Specific Gasification Rate (SGR) $= 255$ (kg/hr/ m^2) (Lubwama, 2010).

2.3.2 Reactor Internal Diameter (D)

The Internal diameter of the reactor was determined using Equation 4.

$$Reactor\ Internal\ Diameter\ (D)(m) = \left[\frac{1.27 \times FCR}{SGR}\right]^{\frac{1}{2}} \qquad (4)$$

2.3.3 Reactor Height

The height of the reactor (H) is affected by the quantity of fuel to be maintained in the reactor, feedstock density and the Specific Gasification rate. It was determined using Equation 5.

$$H = \frac{SGR \times T}{\rho_b} \qquad (5)$$

where:
T = Gasifier Operating time (hr)
ρ_b = Feedstock density (kg/m^3)

2.3.4 Volume of Reactor

The volume of the reactor was determined using Equation 6.

$$V_r = \pi r^2 H \qquad (6)$$

where:

$$r = radius\ of\ the\ reactor$$

2.3.4 Superficial air velocity

The superficial air velocity (V_s) affects the amount of char and tar produced during the gasification process. It is the ratio of the air flow rate at normal conditions to the cross-sectional area of the gasifier. It was determined using Equation 7.

$$V_s = \frac{4 \times AFR}{\pi D^2} \qquad (7)$$

where:

AFR = Air flow Rate (m^3/hr)

2.3.5 Hopper Volume

The Hopper was designed to contain the volume of fuel required by the reactor and the volume of fuel in the reactor less the volume of the reactor. This allows the reactor to operate as a semi-continuous system. The hopper volume was determined using Equations 8 and 9.

$$V_f = \frac{T \times FCR}{\rho_b \times P_f} \qquad (8)$$

where: P_f = $Random\ packing\ factor$, 0.70 $was\ used$ ($Kumar\ et\ al.$, 2018)

$$V_h = V_f + (V_f - V_r) \qquad (9)$$

2.3.6 Optimal Height of the Various Zones of the Reactor

The heights of the drying and pyrolysis, oxidation and reduction zone were determined based on the optimal height of each of the zones relative to the overall reactor height as determined by (Rahman *et al.*, 2021).

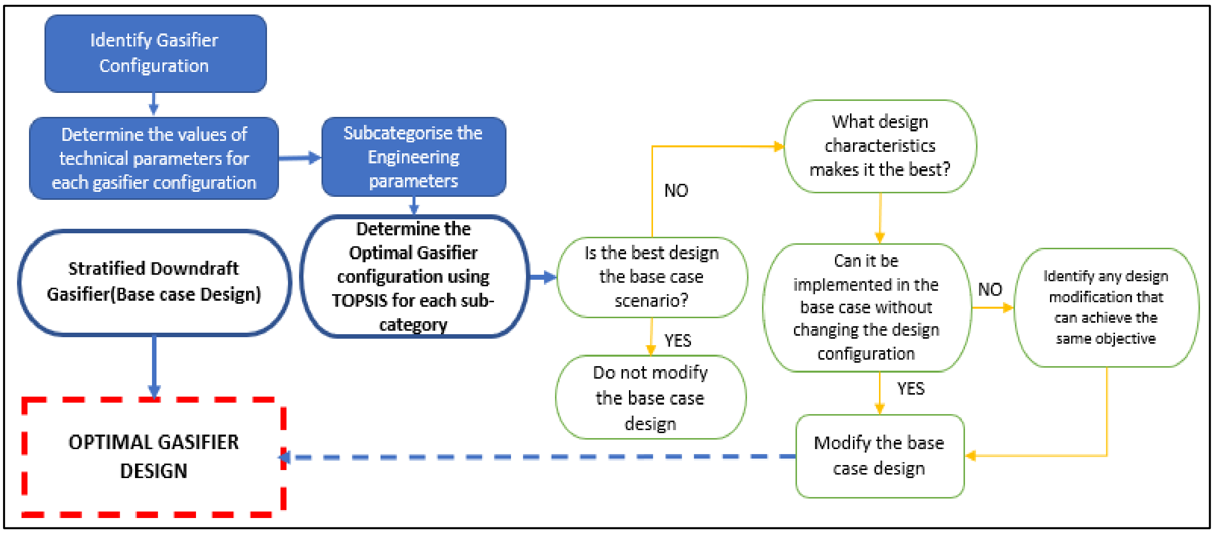

Fig. 3 Schematic for the Design of the Gasifier Reactor

3 Results and Discussion

3.1 Decision Matrix and Ranking of Gasifier Reactor Type Using TOPSIS

The decision matrix for ranking the various gasifier reactor types to meet the user requirement consists of the various gasifier types as the alternatives and the engineering parameters as the decision criteria (see Table 1). The relative weight of the engineering parameters as determined from the relationship between the user requirement was used as the weights in the TOPSIS. To achieve the end user requirement each of the decision criteria is either maximize or minimize (see Table 1). For example, even though low ash content is preferred during gasification, the user requires to use residues with high ash content (due to the high ash content of crop residues) which implies the selection of a gasifier type that can handle high ash content. Moreover, higher moisture content is undesirable in the gasification process, however, the user requires a gasifier type that can use feedstock with higher moisture content, therefore the objective is to maximise.

Osei *et al*. (2022) established that stratified downdraft is the optimal gasifier reactor type for gasification of crop residues in Ghana. The major drawbacks of the stratified downdraft as compared with the other types are lower efficiency resulting from the lack of internal heat exchange as well as lower syngas heating value (Hanif *et al*., 2015). The lower conversion efficiency and difficulties in handling higher moisture content of fuel are also limitations of the stratified downdraft gasifier (Chopra and Jain, 2007). Based on the deficiencies in the base case design (stratified downdraft gasifier), there is a need to therefore modify it in order to develop an optimal gasifier reactor to meet the user requirement. Table 2 presents the closeness to the perfect solution values (CC_i^*) for the various gasifier alternative design under the five engineering sub-categories based on the outcomes of the TOPSIS. Fig. 4 presents the ranks of the various gasifier types based on the CC_i^* values. Updraft gasifier was ranked as the best gasifier type to handle a wide range of fuel characteristics (see Fig. 4) as required by the user i.e wide range of particle size, high moisture content and ability to handle fuel with high ash content. The updraft gasifier can handle fuel with high ash content due to the arrangement of the reaction zones. Due to the configuration of the

updraft gasifier (the reduction zone comes before the combustion) ash from the combustion zone does not impede the reduction process and therefore fuels with higher ash content can be used (Basu, 2018). Equally the updraft configuration can handle fuel with high moisture content due to the countercurrent movement of fresh feedstock and syngas leaving the reactor. High-temperature syngas leaving the reactor dries the fresh feedstock before it enters the reactor (Cerinski, 2021).

Table 2 (CC_i^*) values for Design alternatives

	Sub-category of Engineering Characteristics				
Alternative Designs	**FC**	**EF**	**OP**	**SQ**	**GC**
TD	0.52	0.50	0.75	0.93	0.99
SD	0.52	0.50	0.80	0.95	0.99
UD	0.82	1.00	0.62	0.05	1.00
CD	0.15	0.43	0.62	0.93	0.99
BFG	0.47	0.25	0.80	0.92	0.00
CFG	0.46	0.62	0.74	0.95	0.80
EFG	0.23	0.16	0.37	0.94	0.00

Moreover, due to the counter current movement of syngas and fresh feedstock, the resident time of the feedstocks in the gasifier increases because of resistance in the downward movement of the feedstocks. This allows the Updraft gasifier to handle larger feedstock particle size as a result of effective drying of feedstock. The cross-draft gasifier was identified as the worst gasifier to handle various feedstock characteristics as required by the user. Cross draft gasifier even though part of the fixed bed gasifiers is primarily used for gasifying charcoal with little ash content and therefore not suitable for high ash content crop residues. Aside from the challenges of cross draft in handling crop residues, it also has issues with poor CO_2 reduction high exit gas temperature, and high gas velocity (Hanif *et al*., 2015).

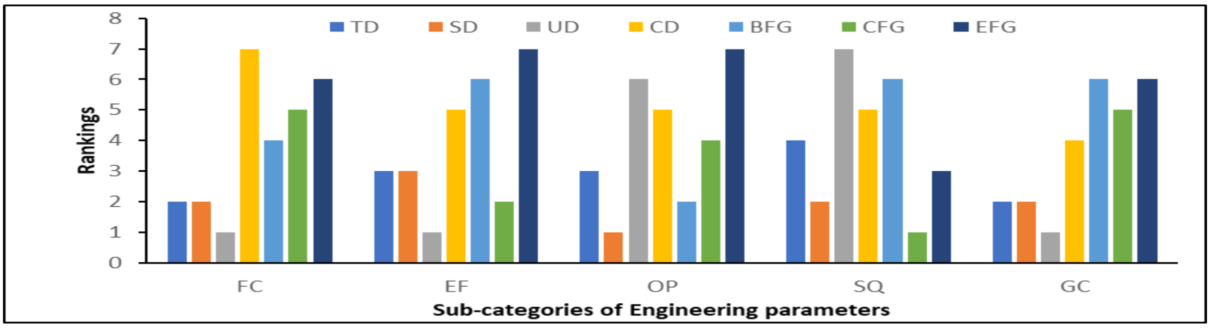

Fig. 4 Ranking of the Various Gasifier Types Under the Various Technical Sub-Categories Parameters

In terms of Efficiency (GTE, CCE, CCE) the updraft gasifier is the optimal gasifier to meet the user's requirement. Among moving bed gasifiers, updraft is the most efficient followed by a downdraft while crossdraft gasifiers are the least efficient (Basu, 2013; Chopra and Jain, 2007). The updraft gasifier utilizes combustion heat very effectively and achieves high cold-gas efficiency due to the low exit temperature of the gas. The high thermal efficiency of the updraft gasifier is also due to the syngas produced transferring its heat to the feedstock when exiting the reactor which results in the drying of the feedstock. High moisture content affects the optimal generation of CH_4, H_2, and CO in the reduction zone and therefore due to the effective drying of feedstocks in the updraft gasifiers high quantities of these syngas components are produced which increases cold gas efficiency. The stratified downdraft gasifier was identified to have the best gasifier operating parameters (OT, OP and ER). Since these characteristics are inherent in the base case design it doesn't require modification. In terms of syngas quality (TC, H_2/CO ratio and HV), the Circulating Fluidized bed gasifier was identified as the best gasifier reactor type. This is due to high operating temperature due to external heating and the use of oxygen and steam as a gasifying agent.

3.2 Design Considerations of the Optimal Gasifier

Based on the best gasifier reactor type under the various sub-categories of the engineering parameters, the base case gasifier designed (stratified downdraft gasifier) was modified using the designed consideration as presented in Table 3. The justification for the various modifications to the base case designs is explained in the subsequent sections.

Table 3 Design Consideration on the Base Case Scenario

Sub-category	Best Ranked Gasifier Type	Parameters	Possible Design modification required on the base case scenario
Feedstock Characteristics (Sub.1)	Updraft gasifier	Ash content (AC)	Increase size of ash bunker
		Moisture content (MC)	Use Screw Auger system to increase fuel retention time
		Particle size (PS)	
Gasifier Efficiency (Sub.2)	Updraft Gasifier	Gasifier thermal efficiency (GTE)	The Use Screw Auger system to increase fuel retention time to ensure effective drying
		Cold gas Efficiency (CGE)	The use of gas recirculation combustor
		Carbon Conversion Efficiency (CCE)	
Operational parameters (Sub.3)	Stratified Downdraft gasifier	Operating temperature (OT)	Does not require modification because it's the base case scenario
		Operating Pressure (OP)	
		Equivalence Ratio (ER)	
Syngas Quality (Sub. 4)	CFG	Tar content (TC)	The use gas recirculating combustor system for thermal tar cracking
		H_2/CO	
		Higher heating Value (HV)	

3.3 Design and components of the Optimal Gasifier Reactor

Based on the outcomes and the consideration of the various design modification as presented in Table 3 and the characteristics of the crop residues considered, a 45 kW semi-continuous stratified downdraft gasifier was designed (see Figs. 5 and 6). In this design, the syngas produced was considered to be used in a 10-kW Compression ignition (CI) engine system with an efficiency of 20 % (Anon. 2021b). The reactor has a fuel consumption rate of 23.00 kg/hr, and an airflow rate of 26.31 m^3/hr (see Table 4). The gasifier reaction zone has a height of 1.7 m, and a volume of 0.17 m^3 (see Fig. 5). It consists of two cylinders with inside and outside diameters of 0.36 and 0.40 m respectively. The gap between the cylinders is packed with fiber glass as insulating material. The gasifier consists of a pyrolysis gas recirculation combustion unit, screw auger system and an extended ash collection bunker. Fig. 7 presents the positions and lengths of the various reaction zones in the gasifier reactor.

During the gasifier operation, feedstocks move downward through the various zones. In the drying zone moisture in the biomass is driven off. During the pyrolysis process, the dried biomass is degraded to char, gases (CO, CO_2, H_2, H_2O, CH_4), bio-oil, and tar vapours. Air enters the gasifier through the nozzle combustor unit. Incoming gasifying air acts as a motive force to suck premixed pyrolysis gas for mixing before combustion. Afterwards, the air pyrolysis gas mixture is combusted inside the combustor. In the reduction zone, char carbon dioxide, water vapour, from the pyrolysis and heat from the combustion zone react through the boudouard reaction, char reforming, water gas shift reaction and methanation reaction to produce CO, H_2, CH_4 and CO_2.

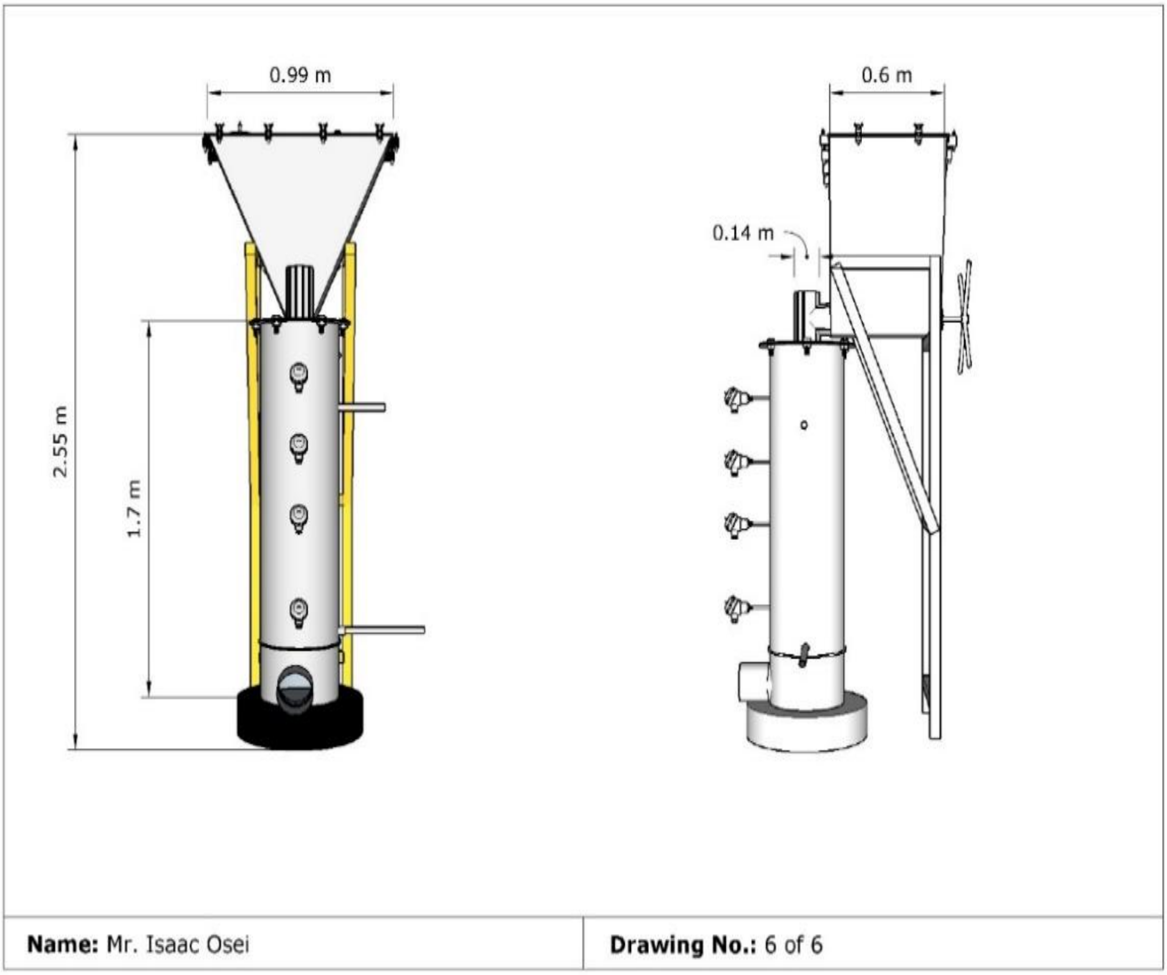

Fig. 5 Schematic Diagram of the Gasifier Reactor

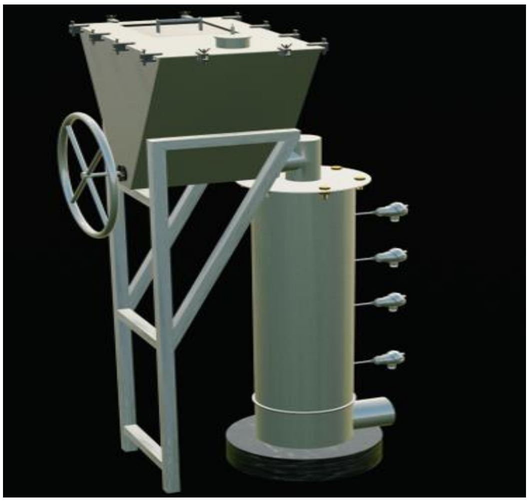

Fig. 6 3D of the Designed Gasifier Reactor

The gasifier was designed to operate as a semi-batch system. For small installation, a batch supply limits the costs related to the management of the installation and reduce the required capital cost needed for automation. The longer residence time of the biomass in the reactor in batch mode allowed better conversion of the fuel and lower tar residues (Manisha, 2013). However, in a batch-feeding system, the introduction of biomass for a new cycle result in a break in the composition of the gas at the start of the cycle before getting good-quality syngas (De Filippis *et al*., 2010). For this reason, a semi-batch system was designed with a hopper volume of 0.27 m^3 (see Fig. 8) which can hold 1.6 times the required volume of fuel in the reactor. The use of a semi-batch system increases the residence time of the feedstock and aid in feedstock drying. It also reduces the frequency of interruption of gas quality due to frequent feeding. Moreover, a semi-batch system produces fewer unburnt by-products with corresponding better conversion efficiency (Zoungrana, 2021). The hopper is made up of 0.32 cm mild steel. The top of the hopper is sealed during operation with a removable plate made up of mild steel.

The hopper cover also contains a 0-15 bar range pressure gauge with a pressure relieve valve of 10 bar. A secondary door is located to provide easy access to the bin. The hopper is trapezoidal with a trough bottom for the auger (see Fig. 9). The side walls of the bin are angled at 30^o to aid in easy downward movement of the feedstock. The base case design was modified with the use of a screw auger system to control feedstock movement into the reactor to ensure a higher feedstock retention time (see Table 4).

Table 4 Design parameters of the Developed Gasifier Reactor

Parameter	Value
Reactor capacity (CSP) (kWe)	45
Reactor Inner diameter (m)	0.36
Reactor Outer diameter (m)	0.40
Reactor total height (m)	1.70
Drying and pyrolysis zone height (m)	0.72
Combustion zone (m)	0.40
Reduction zone (m)	0.32
Air Flow rate (m^3/hr)	26.31
Superficial air velocity (m/hr)	258.45
Fuel consumption rate (kg/hr)	23.00
Specific gasification rate (kg/hr/m^2)	255
Volume of Reactor (m^3)	0.17
Volume of hopper	0.27

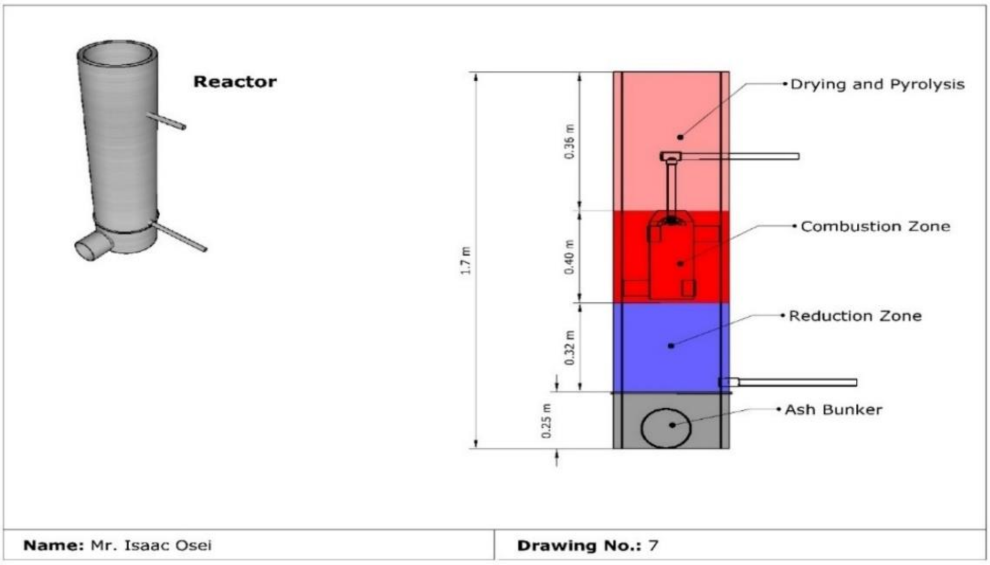

Fig. 7 Reaction Zones of the Designed Gasifier Reactor

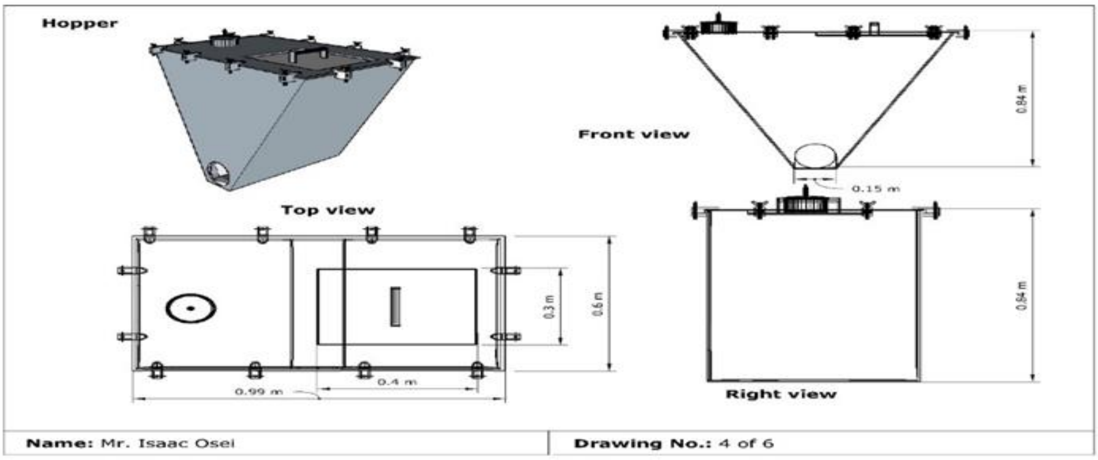

Fig. 8: Schematic Diagram of Gasifier Hopper Assembly

Fig. 10 presents a schematic diagram of a screw auger system with corresponding dimensions. It has an auger shaft diameter, of 2.5 cm and a length of 75 cm which extends to the edge of the gasifier reactor. The pitch and auger flighting diameters are 15 and 14 cm respectively. The auger is manually driven with a hand crank wheel on the outside end of the bin (see Fig. 15). The auger assembly systems allow the feedstock in the gasifier to be controlled. As indicated earlier, the longer residence time of the fuel in the reactor allows for effective drying of the feedstocks and improves the thermal and conversion efficiency during gasification (Cerinski *et al*., 2021). The base case design was also modified to ensure the gasification of feedstock with high ash content. Effective removal of ash from the reactor allows the gasifier to gasify high ash-content fuel (Basu, 2018). An extended ash bunker with a height and diameter of 0.25 and 0.36 m respectively was designed. The fuel is held on an ash grate with circular holes of 0.005 m in diameter.

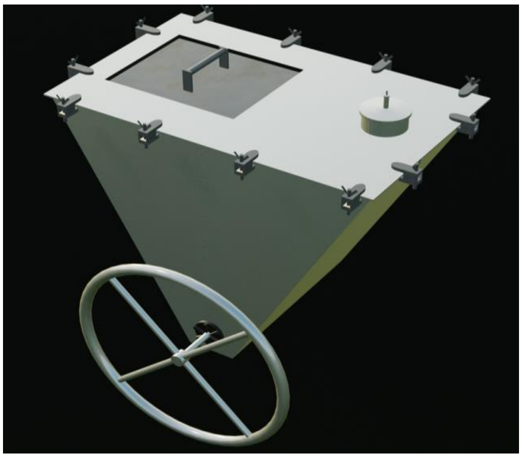

Fig. 9 Hopper Assembly

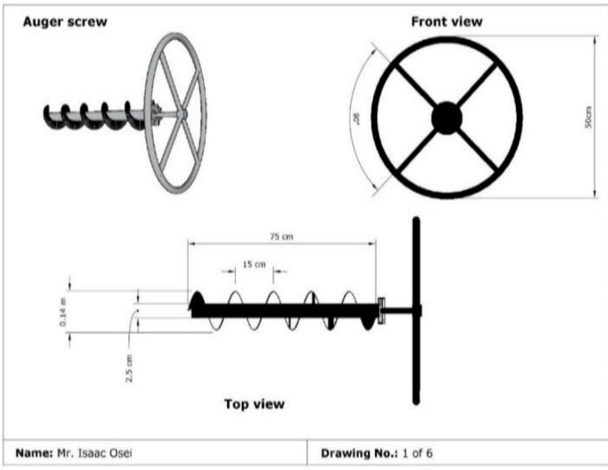

Fig. 10 Schematic Diagram of Gasifier Screw Auger System

In order to improve the syngas quality (tar content, H_2/CO ratio and heating value) and Gasifier efficiency (GTE, CGE, CCE) a combustor gas recirculation is proposed as a design modification of to the traditional stratified downdraft gasifier (see Table 4). Several studies have introduced gasifier modifications to reduce tar content and improve efficiency by introducing changes in gasification conditions and reactions within the gasifier reactor. There are different methods available such as appropriate selection of operating parameters, pyrolysis gas recirculation system, and gasifier modification (Surjosatyo *et al*., 2010). Among the various approaches the use of a nozzle and combustor inside the partial oxidation zone which results in the recirculation of pyrolysis gas resulting has been reported to be effective (Brandt *et al*., 2000; Henriksen *et al*., 2006). Rahman *et al.* (2021) developed an inclined nozzle and a combustor unit for the recirculation of pyrolysis products. In this design, incoming gasifying air acts as a motive force to suck premixed pyrolysis gas for mixing before combustion. Afterwards, the air pyrolysis gas mixture is combusted inside a combustor. The outcome of their study presented a minimum tar range between 7.4 to 27.1 mg/Nm^3 with tar removal efficiency from pyrolysis and syngas of 84.9 and 99.1% respectively. A typical stratified downdraft gasifier produces 1340 mg/Nm^3 (Gautam *et al*., 2011) which is fifty times higher than reported tar produced in the use of combustor recirculation gasifier systems. The low tar content in this design is a result of thermal tar cracking inside the combustor unit. Based on the effectiveness of this approach to reducing tar content and increasing gasifier efficiency the use of a combustor recirculation system was added to the base case design.

Fig. 11 presents the schematic diagram of the gasifier reactor and the combustor assembly. A combustor with a height and outside diameter of 0.40 m and 0.16 m respectively was designed (see Fig. 12). It has a tangential inlet at the top and a cylindrical outlet at the bottom. The combustor has four fins that hold it inside the reactor. Three converging-diverging nozzles are connected 120° from each to an air inlet system for the supply of air into the reactor (see Fig. 12). To avoid a reduction of the temperature due to the entrance of cold gasifying air in the combustor, the designed nozzle inclination system provides a swirling airflow, that increases the residence time of the mixed air-pyrolysis gas inside the combustor. Reduction in tar content has been linked to improving gasifier reactor efficiency and high syngas quality. Low tar content results in high gasifier thermal efficiency, operating temperature, cold gas efficiency, carbon conversion efficiency and heating value. Therefore, higher values of these parameters are expected with low tar generation.

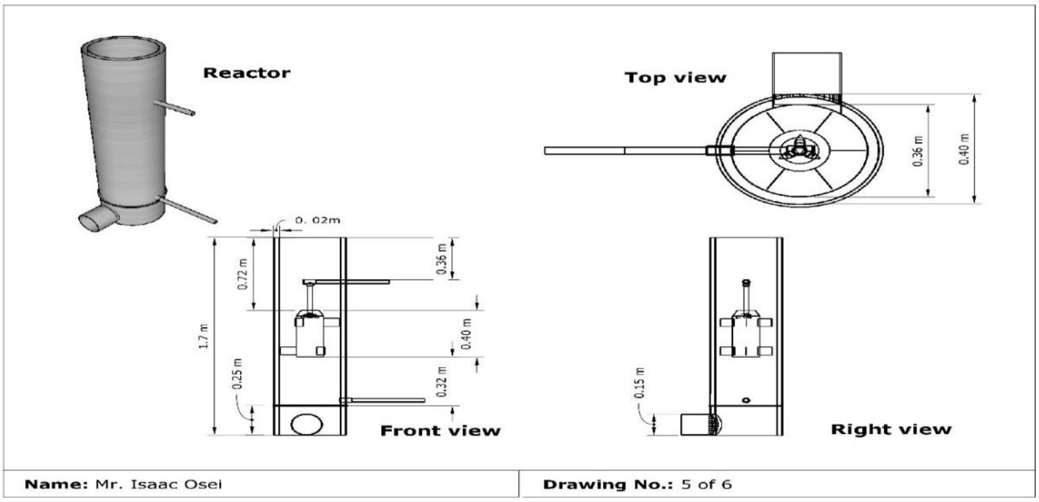

Fig. 11 Schematic Diagram of the Gasifier Reactor and Combustor Assembly

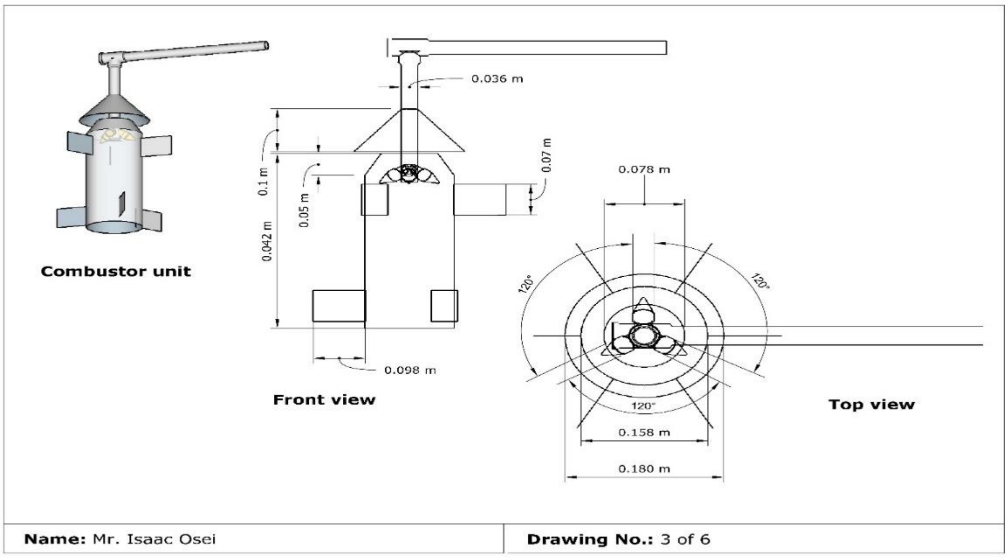

Fig. 12 Schematic Diagram of the Combustor and Nozzle Assembly

4 Conclusions and Recommendations

The aim of this study is to design an optimal gasifier reactor for the gasification of crop residues using Integrated Multicriterial Decision Making (MCDM) Techniques and Quality Function Deployment (QFD) methodological approach. The MCDM/QFD framework consists of user requirement, engineering parameters and seven gasifier types. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was used to rank the various gasifier types based on the thirteen technical parameters. The engineering parameters were further categorised under five sections and the best gasifier type under each category were determined using TOPSIS. The base case design was modified based on the best gasifier reactor type under each category. The study revealed that updraft gasifier is the optimal gasifier that is efficient and can handle wide range of feedstock characteristics. Similarly, stratified downdraft and circulating fluidized bed gasifier are the optimal in terms gasifier operating conditions and good syngas quality respectively. A 45-kW semi-batch stratified Downdraft (SD) Gasifier with internal diameter and height of 0.36 m and 1.7 m respectively were designed based on average fuel consumption of 23 kg/hr and an airflow rate of 26.31 m^3/hr. The optimal gasifier designed from modification of stratified downdraft gasifier consists of a screw auger system, an extended ash collection bunker, and a gas recirculation combustion unit which embeds the characteristics of the optimal gasifier reactor type under each category. As part of further studies, the designed gasifier reactor should be constructed and subjected to a laboratory experiment.

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