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Optimum Design and Parameterization of Downdraft Gasifier: A Multiple Input and Single Output Strategy

Onep Samuel George[1*], Stephen Ndubuisi Nnamchi[2] and Dennison Selvam Milon[1]

[1]Department of Mechanical Engineering, SEAS, Kampala International University, Uganda

[2]Department of Mechanical and Industrial Engineering, FAST, Mbarara University of Science and Technology, Uganda

***Corresponding Author:** Onep Samuel George, Department of Mechanical Engineering, SEAS, Kampala International University, Uganda.

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Abstract
This paper considers optimum design and parameterization of downdraft gasifier as a sure way to improve its performance, besides, improving the quality of biomass feedstock. The poor performance of gasifiers and gasification could be attributed to a lack of appropriate system optimization. Thus, this paper employs a multiple input single output (MISO) strategy to achieve optimum design of variables and functions by assembling and coupling design functions to a single unconstrained objective function, which yields the optimum design variables and functions. Additionally, the downdraft gasifier's design optimization and parameterization produced auxiliary optimal design variables and functions as well as an optimal system efficiency of 53%. MISO is a viable optimization strategy for upgrading single input single output (SISO) designs to an optimum design for improved system performance. Although gasifier height affected the optimality of other design variables and functions, it should not be considered a design function since it negated optimization and parameterization. It is therefore advised that the designer fix it.

Keywords: Optimum Design, Parameterization, Downdraft Gasifier, Miso, Design Functions, Variables

Introduction
Design has been a long age practice, which designers capitalize on the causal relationship exiting between the designs variables (dependent and independent). The current state of the art considers causal relationship as the design functions. Thus, the design functions relate the major design parameter with the influential design variables. The design functions are established by physical laws governing the behavior of the process and system generally [1,2]. Whereas some design functions are empirically established from experimental data relating the design function with the sensitive design variables [3]. Besides, a functional design function is developed on the performance data of an existing real system by plotting the essential historic input and output data [1,4]. Such plots indicate the ceiling values for safe and economic operations of the systems in order to guard against wastage of resources [5]. The long age design techniques is based on a staged designs, a single design function is considered at a time in an isolation other design functions, subsequently, the output is connected to another design function until the system design is completed. This form of design is known as a single input single out, SISO design technique, which is void of optimum system performance in their quest to improve system performance, propounded aggregation of design functions for the optimum performance of thermal system, which aligns with the multiple inputs and multiple outputs, MIMO of the entire design variables. However, this technique is onerous and causes computational system errors in phase of colossal design functions and variables [6-10]. The present work modifies the MIMO to another design approach, which uses multiple input and single output, MISO via coupling of the design functions to eliminate the erroneous behavior of the computational tools encountered in MIMO.

In addition, many literature propose design as a premium way to enhance system performance as highlighted; Susastriawan and Saptoadi asserted that the quality and efficiency of producer gas in downdraft gasifier are influenced by nature of biomass feedstock, process conditions and crucial gasifier designs; Patra and Sheth consolidated gasifier design with mathematical models as a means of achieving significantly improvement; Li et al. employed designs to achieve appreciable gasification performance, carbon conversion and biomass gasification efficiencies; Wang et al. synergized building cooling, heating, and power (BCHP) designs to save 45.4% annual total cost (ATC) and to emit less CO2; Yan, et al. suggested that the performance of biomass gasification is controlled to a larger extent by the gasifier design; Ruiz et al. made improvements in gasifier performance through design and optimal operating condition; Thomson et al. proposed that gasifier product yield is influenced by its design and operating circumstances [6-8,11-14]. Through design modification and optimization, Li, et al. demonstrated the potential for improvement in the lower heating value of the product gas, oxidation temperature and the gasification intensity [6].

Classically, Akhator et al. combined Imbert and stratified models with designs to achieve a good syngas yield. Roslee et al. merely developed and tested a small-scale downdraft gasifier with 71% efficiency using empty fruit bunch pellets [15,16]. Preliminarily, Ingle and Lakade developed 20 KW downdraft gasifier for heating a furnace using wood blocks of varying sizes, however, smaller wood blocks engendered higher calorific values [17]. On the other hand, Kailasnath et al. achieved 80% gasification efficiency with an undemystified design technique, which was based on non-linear extrapolation of literature data [18]. Moreover, Susastriawan and Saptoadi showed that gasifier design is more crucial in gasification process compared to characterization of biomass feedstock and process parameters [11]. Pertinently, Patra and Sheth combined mathematical model and empirical designs in developing gasifier reactor [12]. Notably, Jahromi et al. and Li et al. engaged simulations as veritable tool for the preliminary design of gasifier [6,19]. Uniquely, Wang et al. implemented genetic algorithm in developing efficient biomass gasifier. Innovatively, Yan, et al. introduced semi-empirical T-ANN model instead of empirical model in improving gasifier design and operation [7,13]. Exceptionally, Ramos et al. and Ruiz et al. outlined nondimensional factors inherent in the design and operation of gasification plants. Rahman et al. advocates for fixed bed downdraft gasifier designs instead of moving bed downdraft gasifier in order to minimize tar formation [14,20,21]. Economically, Thomson et al. developed a cost competitive gasifier with high profitability index relative to fossil resources. Ojolo and Orisaleye suggested using the forced downdraft mode of operation with an empirically designed laboratory-scale gasifier in order to achieve improved results [8,22]. Through design and structural optimization, Li et al. was able to improve on the lower heating value of the product gas, oxidation temperature and the gasification intensity [23].

Overview of numerical results of gasifier design is presented for comparison of the literature and the present study. Thus, Guangul et al. obtained equivalent ratio, ER of 0.3 gasification efficiency of 0.7 , specific gasification rate of 0.04167 kg/s.m^2 and fuel consumption rate of 0.00278 kg/s [24-26]. Comprehensively, Susastriawan & Saptoadi reviewed the performance of a number of gasifiers and reported values: height of gasifiers, 0.6 to 1.02 m; Biomass feed-rate, 0.00028 to 0.00083 kg/s; air flow rate, 0.00083 to 0.00792 m^3/s; equivalent ratio, 0.18 to 0.45; diameter of throat, 0.1 to 0.3 m; height of throat, 0.1 to 0.5 m; diameter of air tube, 0.005 to 0.025 m; diameter of gasifier tube, 0.1 to 0.4 m; efficiency, 0.711 to 0.822; critical thickness of insulation, 0.003 to 0.05 m; and specific gasification rate, 0.044 kg/s.m^2. Also, Jahromi et al. presented values for maximum conversion efficiency as 0.69 and inlet velocity as 20 m/s [11,19]. Whilst, Wang et al. on the other hand, showed that cold gas efficiency was 0.66, and the system's gross thermal efficiency was given at 0.27 [27]. However, the design results show that the lower heating value of syngas (increased by 6.95%), syngas yield (increased by 1.9%) and cold gas efficiency (increased by 8.3%) according to Yan, et al. [7]. Accordance with Rahman et al., equivalence ratio lies between 0.29 and 0.41, while the average gasifier cold gas efficiency is 0.605 to 0. 827 [21]. In addition, Thomson et al. suggested cold gas efficiency of 0.75 to 0.9 and carbon conversion efficiency of 0.9 to 1.0. Pertinently, Ojolo and Orisaleye using designed laboratory scale gasifier with reactor and throat diameters of 0.238 m and 0.068 m respectively and five air nozzles (each 0.01 m diameter), reported fuel conversion rate of 0.00111kg/s, when using palm kernel shells as fuel in forced downdraft mode [8,22]. On the other hand, Li, et al. found the lower heating value maximized at 4380 kJ/m3 at a gasification rate of 0.0161 kg/s/m^2 at specified air flow rate of 0.00053 m^3/s [23].

Overview of literature show that the existing design are mostly centered on the unit synthesis of the biomass chain products with little or no emphasis on the unit operations, which captures the process or thermal equipment and the external forces influencing the efficient performance of the gasifier [6-8,11-23]. Besides, neglecting the unit operations, they are scarcely optimized, thus, leading to low performance of the gasifier. The present study attempts to improve the gasifier design and operation by introducing a MISO design technique which caters for both unit synthesis and unit operation of biomass gasifier. The MISO design technique in align to literature engenders evolutions in gasifier (unit operation) and gasification process (unit synthesis) [6-8,11-14].

Materials And Methods

The design is centered on optimization of conventional design of downdraft gasifier, design functions and variables were identified. The optimization is initiated by assembling the design functions with the corresponding variables. The design objective function is developed by coupling the design functions either in linear or non-linear order to obtain the modified objective function. The modified function is differentiated with respect to design function to obtain the optimum value of the design function and the corresponding variables, using combined scheme (Nnamchi-Onep scheme, defined in the flow chart (Figure 1) and algorithm (design procedures)

Design Basis and Considerations

A pilot gasifier is optimized such that it outputs 5000 Watts of power from conversion of biomass feed (wood chippings), agricultural and municipal solid wastes. Conventional design functions employed for SISO design are to be coupled to formulate a modified (coupled) design function, the optimization tailors to MISO according to Nnamchi-Onep scheme portrayed in design procedures and design formulatio for generating optimum functions and variables of SISO design parameters.

Design Procedures

Achieving the best possible design for the downdraft gasifier unit requires the completion of the following actions or tasks:

- Assemble the functions or formulas for the design;
- Couple the pivot variable, pv (the dependent variable of the coupled functions) with the design equations or functions (g);

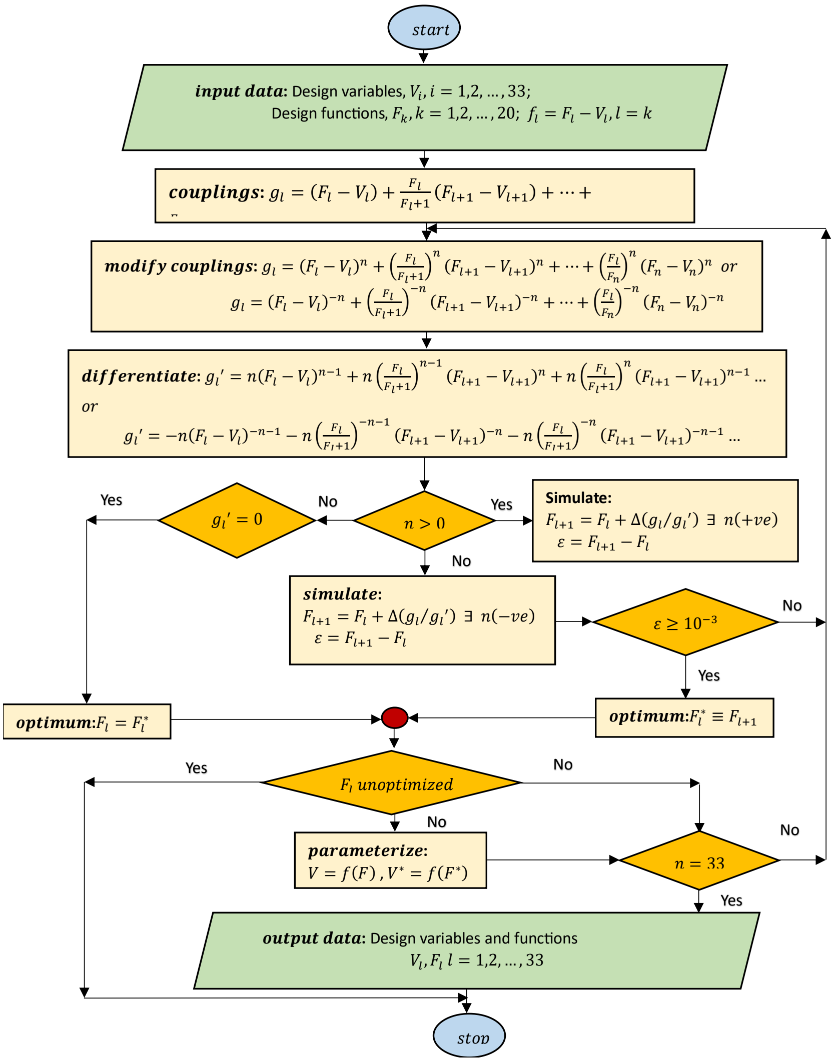

Figure 1: Design Flowchart of Biomass Gasifier According to Nnamchi-Onep Scheme

- Differentiate the modified functions in item 3 with respect to pivot variable $\left(g' = \frac{\partial g_{mod}}{\partial pv}\right)$;
- Substitute the design variables into g_{mod} and g' to obtain their numerical values;
- Define the change in pivot variable ($\Delta pv = g_{mod}/g'$);
- Iterate the future values of pv ($pv_{i+1} = pv_i + \Delta pv$);
- Seek for convergence (ε) of pv ($\varepsilon = pv_{i+1} - pv_i$);
- Whereby pv is defined by single design variable, then, parameterize, else, don't parameterize;
- Plot pv against function $gmod, or\ g'\ or\ \varepsilon$;
- Add trend line to plot of pv;
- Differentiate the trend line equation to establish the turning point and the optimum pv;
- Scale optimum pv to appropriate size with an arbitrary number;
- Then, the procedures terminates with optimum design variables of the downdraft gasifier.
- The design procedure is illustrated in the design flowchart (Figure 1)

Design Flowchart

The biomass gasifier design flowchart in Figure 1, guided by Nnamchi-Onep scheme, presents sequential design procedures, which starts with imputing the input data and running it to produce optimization and parameterization resulting on meeting the convergence criterion.

Design Formulation

Sample optimization and parameterization of the design functions and variables are demonstrated with the gasifier throat diameter, d_{th}; with the corresponding design function, g_1 in Eq. (1)

$$g_j = F_j - f(V_k) \ \exists \ j = k = 1 \ ; \ g_1 = d_{th} - \left(\frac{4A_{th}}{\pi}\right)^{0.5} \tag{1}$$

Where F is the design function and V is the design variable.
The syngas generation design function, SG is given in Eq.(2)

$$g_j = F_j - f(V_k) \ \exists \ j = k = 2 \ ; \ g_2 = SG - \frac{P_w}{\rho_{syn,cri}\, LHV} \tag{2}$$

The throat height design function, H_{th} is defined in Eq.(3)

$$g_j = F_j - f(V_k) \ \exists \ j = k = 3 \ ; \ g_3 = H_{th} - 1.5d_{th} \tag{3}$$

The equivalent ratio design function, ER is expressed in Eq.(4)

$$g_j = F_j - f(V_k) \ \exists \ j = k = 4 \ ; \ g_4 = H_{th} - 1.5d_{th} \tag{4}$$

The superficial velocity design function, V_s is expressed in Eq.(5)

$$g_j = F_j - f(V_k) \ \exists \ j = 5, \ k = \{6,14\} \ ; \ g_5 = V_s - \frac{4\,SG}{\pi D_g^2} \tag{5}$$

The diameter of syngas outlet nozzle design function, D_g is stated in Eq.(6)

$$g_j = F_j - f(V_k) \ \exists \ j = 6, \ k = \{6,8\} \ ; \ g_6 = D_g - \left(\frac{4\,SG}{\pi V_s}\right)^{0.5} \tag{6}$$

The height of the gasifier design function, H_g is specified in Eq.(7)

$$g_j = F_j - f(V_k) \ \exists \ j = 7, \ k = \{9,10\} \ ; \ g_7 = H_g - SGR \times t \tag{7}$$

The thermal power output design function, P_w is described in Eq.(8)

$$g_j = F_j - f(V_k) \ \exists \ j = 8, \ k = 6 \ ; \ g_8 = P_w - \rho_{syn,cri}\, LHV\, SG \tag{8}$$

The diameter of gasifier tube design function, D is written in Eq.(9)

$$g_j = F_j - f(V_k) \ \exists \ j = 9, \ k = \{9,11\} \ ; \ g_9 = D - \left(\frac{1.27\,FCR}{\rho_f\, SGR}\right)^{0.5} \tag{9}$$

The fuel consumption rate design function, FCR is given in Eq.(10)

$$g_j = F_j - f(V_k) \ \exists \ j = 10, \ k = \{2,9,12,13,14\} \ ; \ g_{10} = FCR - 0.5\left(\frac{P_w}{cv\eta} + \frac{\pi\, SGR\, D^2}{4}\right) \tag{10}$$

The diameter of air tube design function, D_t is specified in Eq.(11)

$$g_j = F_j - f(V_k) \ \exists \ j = 11,\ k = \{15, 16, 17\} \ ; \ g_{11} = D_t - \left(\frac{1.27 \dot{V}_a}{vZ} \right)^{0.5} \tag{11}$$

The specific gasification rate design function, SGR is indicated in Eq.(12)

$$g_j = F_j - f(V_k) \ \exists \ j = 12,\ k = \{11, 18\} \ ; \ g_{12} = SGR - \frac{FCR}{A_r} \tag{12}$$

The critical thickness of insulation design function, C_t is shown in Eq.(13)

$$g_j = F_j - f(V_k) \ \exists \ j = 13,\ k = \{19, 20\} \ ; \ g_{13} = C_t - \frac{k}{h} \tag{13}$$

The mass flowrate of air design function, $\dot{m}a$ is shown in Eq.(14)

$$g_j = F_j - f(V_k) \ \exists \ j = 14,\ k = \{2, 4, 12, 13\} \ ; \ g_{14} = \dot{m}_a - \frac{afa\, P_w}{cv\eta} \tag{14}$$

The diameter of reactor hopper design function, D_h is presented in Eq.(15)

$$g_j = F_j - f(V_k) \ \exists \ j = 15,\ k = 21 \ ; \ g_{15} = D_h - \left(\frac{4 A_h}{\pi} \right)^{0.5} \tag{15}$$

The specific biomass feed rate function, SFR is displayed in Eq.(16)

$$g_j = F_j - f(V_k) \ \exists \ j = 16,\ k = \{18, 22\} \ ; \ g_{16} = SFR - \frac{\dot{m}_f}{A_r} \tag{16}$$

The air flowrate function, $AFLR$ is given in Eq.(17)

$$g_j = F_j - f(V_k) \ \exists \ j = 17,\ k = \{5, 11, 23, 24\} \ ; \ g_{17} = AFLR - \frac{ER\, FCR\, afs}{\rho_a} \tag{17}$$

The efficiency of gasifier design function, η is described in Eq.(18)

$$g_j = F_j - f(V_k) \ \exists \ j = 18,\ k = \{2, 4, 12, 25\} \ ; \ g_{18} = \eta - \frac{afa\, P_w}{cv\, \dot{m}_a} \tag{18}$$

Design objective function is based on Eqs. [1-18] by coupling them with n-order in Eqs. [19a,19b] to obtained a general coupled design objective function, $g_{coupled}$ in Eq.(19a)

$$g_{coupled} = (F_j - f(V_k))^n + \left(\frac{F_j}{F_{j+1}} \right)^n (F_{j+1} - f(V_{k+1}))^n + \cdots + \left(\frac{F_j}{F_N} \right)^n (F_N - f(V_N))^n \quad \exists \quad -5 \le n \le 5, \quad N = 18 \tag{19a}$$

The specific coupled function (d_{th}) in Eq.(19b)

$$\begin{aligned} g_{coupled} = & \left(d_{th} - \left(\frac{4A_{th}}{\pi} \right)^{0.5} \right)^n + \left(\frac{d_{th}}{SG} \right)^n \left(SG - \frac{P_w}{\rho_{syn,cri} LVH} \right)^n + \left(\frac{d_{th}}{H_{th}} \right)^n (H_{th} - 1.5 d_{th})^n + \left(\frac{d_{th}}{ER} \right)^n \left(ER - \frac{afa}{afs} \right)^n + \left(\frac{d_{th}}{V_s} \right)^n \left(V_s - \frac{4SG}{\pi D_g^2} \right)^n \\ & + \left(\frac{d_{th}}{D_g} \right)^n \left(D_g - \left(\frac{4SG}{\pi V_s} \right)^{0.5} \right)^n + \left(\frac{d_{th}}{H_g} \right)^n (H_g - SGRt)^n + \left(\frac{d_{th}}{P_w} \right)^n (P_w - \rho_{syn,cri} LHV\, SG)^n + \left(\frac{d_{th}}{D} \right)^n \left(D - \left(\frac{1.27 FCR}{\rho_f\, SGR} \right)^{0.5} \right)^n \\ & + \left(\frac{d_{th}}{FCR} \right)^n \left(FCR - 0.5 \left(\frac{P_w}{cv\eta} + \frac{\pi\, SGR\, D^2}{4} \right) \right)^n + \left(\frac{d_{th}}{D_t} \right)^n \left(D_t - \left(\frac{1.27 \dot{V}_a}{vZ} \right)^{0.5} \right)^n + \left(\frac{d_{th}}{SGR} \right)^n \left(SGR - \frac{FCR}{A_r} \right)^n + \left(\frac{d_{th}}{C_t} \right)^n \left(C_t - \frac{k}{h} \right)^n \\ & + \left(\frac{d_{th}}{\dot{m}_a} \right)^n \left(\dot{m}_a - \frac{afa\, P_w}{cv\eta} \right)^n + \left(\frac{d_{th}}{D_h} \right)^n \left(D_h - \left(\frac{4A_h}{\pi} \right)^{0.5} \right)^n + \left(\frac{d_{th}}{SFR} \right)^n \left(SFR - \frac{\dot{m}_f}{A_r} \right)^n + \left(\frac{d_{th}}{AFLR} \right)^n \left(AFLR - \frac{ER\, FCR\, afs}{\rho_a} \right)^n \\ & + \left(\frac{d_{th}}{\eta} \right)^n \left(\eta - \frac{afa\, P_w}{cv\, \dot{m}_a} \right)^n \quad \exists \quad -5 \le n \le 5 \end{aligned} \tag{19b}$$

Coupled objective function in Eqs. (19a and19b) is differentiated with respect to the design function (throat diameter, d_{th}) in Eq. (20)

$$
\begin{aligned}
g'_{coupled} = \left(\frac{d_g}{d_{th}}\right) = \left(2d_{th} - 2.256304300\sqrt{A_{th}}\right) + \frac{2d_{th}\left(SG - \dfrac{P_w}{\rho_{syn,cri}\,LHV}\right)^2}{SG^2} + \left(\left(\frac{2d_{th}\left(H_{th} - 1.5d_{th}\right)^2}{H_{th}^2}\right) - \left(\frac{3d_{th}\left(H_{th} - 1.5d_{th}\right)^2}{H_{th}^2}\right)\right) \\
+ \left(\frac{2d_{th}\left(ER - \dfrac{afa}{afs}\right)^2}{ER^2}\right) + \left(\frac{2d_{th}\left(V_s - \dfrac{4SG}{\pi D_g^2}\right)}{V_s^2}\right) + \left(\frac{2d_{th}\left(D_g - 1.128152150\sqrt{\dfrac{SG}{V_s}}\right)^2}{D_g^2}\right) + \left(\frac{2d_{th}\left(H_g - SGRt\right)^2}{H_g^2}\right) + \left(\frac{2d_{th}\left(P_w - \rho_{syn,cri}\,LHV\,SG\right)}{P_w^2}\right) \\
+ \left(\frac{2d_{th}\left(D - 1.126942767\sqrt{\dfrac{FCR}{\rho_f\,SGR}}\right)^2}{D^2}\right) + \left(\frac{2d_{th}\left(FCR - \dfrac{0.5P_w}{cv\eta} - 0.3928571429\,SGR\,D^2\right)^2}{FCR^2}\right) + \left(\frac{2d_{th}\left(D_t - 1.126942767\sqrt{\dfrac{\dot{v}_a}{vZ}}\right)^2}{D_t^2}\right) \\
+ \left(\frac{2d_{th}\left(SGR - \dfrac{FCR}{A_r}\right)^2}{SGR^2}\right) + \left(\frac{2d_{th}\left(C_t - \dfrac{k}{h}\right)^2}{C_t^2}\right) + \left(\frac{2d_{th}\left(\dot{m}_a - \dfrac{afa\,P_w}{cv\eta}\right)^2}{\dot{m}_a^2}\right) + \left(\frac{2d_{th}\left(D_h - \dfrac{\sqrt{154\sqrt{A_h}}}{11}\right)^2}{D_h^2}\right) + \left(\frac{2d_{th}\left(SFR - \dfrac{\dot{m}_f}{A_r}\right)^2}{SFR^2}\right) \\
+ \left(\frac{2d_{th}\left(AFLR - \dfrac{ER\,FCR\,afs}{\rho_a}\right)^2}{AFLR^2}\right) + \left(\frac{2d_{th}\left(\eta - \dfrac{afa\,P_w}{cv\,\dot{m}_a}\right)^2}{\eta^2}\right) \ \exists \quad n = 2 \ni
\end{aligned}
\tag{20}
$$

The change in design function, ΔF_j is given in Eq.(21) as

$$\Delta F_j = \frac{g_{coupled}}{g'_{coupled}} \tag{21}$$

Future design function, F_{j+1} is defined in Eq.(22)

$$F_{j+1} = F_j + \Delta F_j = F_j + \frac{g_{coupled}}{g'_{coupled}} \tag{22}$$

The convergence criterion, ε is expressed in Eq.(23)

$$\varepsilon = F_{j+1} - F_j \leq 10^{-3} \tag{23}$$

The parameterization of design variable, V is possible as a lone variable

$$F_j = d_{th} - \left(\frac{4A_{th}}{\pi}\right)^{0.5} \text{ or } V_k = A_{th} - \left(\frac{\pi d_{th}^2}{4}\right) \ \exists \ j = k = 1 \tag{24}$$

Optimization and parameterization of other design functions follow the same procedure above.

Design Input Data

The necessary information (data) needed for the optimum design of gasifier is listed in Table 1 in system international, SI unit, which was adopted in the computations leading to optimum values of the under listed design variables. Also, Table 1 contains design equations with the assigned design functions and variables used in the optimization of the gasifier (the design functions and variables were 18 and 25 respectively), with the relevant sources itemized.

S#	Parameter	Value	SI_value	Unit	Design equation	Design function, F	Design variables, V	Source
1.	Diameter of throat, d_{th} (cm)	9.1	21.4503	m	Eq.(1)	$F_1 \equiv d_{th}$	$V1 \equiv A_{th}$	Gado et al. [28]
2.	Syngas Generation Rate, SG (m^3/hr)	13	0.00361	m^3/s	Eq.(2)	$F2 \equiv SG$	$V2 \equiv P_w$	Akhator et al. [15]
3.	Throat height, H_{th} (cm)	13.7	0.1370	m	Eq.(3)	$F_3 \equiv H_{th}$	$V_3 \equiv d_{th}$	Gado et al. [28]
4.	Equivalent Ratio	0.4	0.4000		Eq.(4)	$F_4 \equiv ER$	$V_4 \equiv afa$, $V_5 \equiv afs$	Akhator et al. [15]
5.	Superficial velocity, V_s (m/s)	4523.0	1.2564	m/s	Eq.(5)	$F_5 \equiv V_s$	$V_6 \equiv SG$, $V_7 \equiv D_a$	Belonio [29]
6.	Diameter of Syngas Outlet Nozzle, D_g (cm)	4	0.0400	m	Eq.(6)	$F_6 \equiv D_g$	$V_6 \equiv SG$, $V_8 \equiv V_s$	Akhator et al. [15]

7.	Height of the gasifier, H_g (mm)	1100	1.100	m	Eq.(7)	$F7 \equiv H_g$	$V_9 \equiv SGR$, $V_{10} \equiv t$	Susastriawan et al. [30]
8.	Thermal Power Output, P_w (KW)	5	5000	W	Eq.(8)	$F_8 \equiv P_w$	$V_6 \equiv SG$	Akhator et al. [15]
9.	Diameter of Gasifier tube, D (m)	0.31	0.31	m	Eq.(9)	F_9≡D	$V_{11} \equiv FCR$, $V_9 \equiv SGR$	Wiyono et al. [31]
10.	Fuel Consumption Rate, FCR (kg/hr)	0.9461	0.000263	kg/s	Eq.(10)	$F_{10} \equiv$FCR	$V_2 \equiv Pw$,$V_9 \equiv SGR$, $V_{12} \equiv cv$, $V_{13} \equiv \eta$, $V_{14} \equiv D$	Belonio [29]
11.	Diameter of Air Tube, D_t (cm)	13.7	0.137	m	Eq.(11)	$F_{11} \equiv D_t$	$V_{15} \equiv \dot{V}_a$, $V_{16} \equiv V$, $V_{17} \equiv Z$	Wiyono et al. [31]
12.	Specific Gasification Rate, SGR(m^3/m^2hr)	2,000	0.556	m^3/m^2s	Eq.(12)	$F_{12} \equiv$SGR	$V_{11} \equiv FCR$,$V_{18} \equiv A_r$	Akhator et al. [15]
13.	Critical Thickness of Insulation, C_t (mm)	7	0.007	m	Eq.(13)	$F_{13} \equiv C_t$	$V_{19} \equiv k$, $V_{20} \equiv h$	Belonio [29]
14.	Mass flowrate of air, $\dot{m}_a$ (kg/s)	0.842	0.842	kg/s	Eq.(14)	$F_{14} \equiv \dot{m}_a$	$V_2 \equiv Pw$, $V_4 \equiv afa$, $V_{12} \equiv cv$, $V_{13} \equiv \eta$	Belonio [29]
15.	Diameter of Reactor Hopper, D_h (cm)	6.94	0.0694	m	Eq.(15)	$F_{15} \equiv D_h$	$V_{21} \equiv A_h$	Chawdhury and Mahkamov [32]
16.	Specific Biomass feed rate (SFR) ($Kg/m^2/s$)	0.00348	0.0444	Kg/m^2s	Eq.(16)	$F_{16} \equiv$SFR	$V_{18} \equiv A_r$, $V_{22} \equiv \dot{m}_f$	Wiyono et al. [31]
17.	Air Flow Rate, AFLR (m^3/hr)	2.121	0.000589	m^3/s	Eq.(17)	$F_{17} \equiv$AFLR	$V_5 \equiv afs$, $V_{11} \equiv FCR$, $V_{23} \equiv ER$, $V_{24} \equiv \rho_a$	Susastriawan et al. [30]
18.	Efficiency, η	0.6	0.6	%	Eq.(18)	$F_{18} \equiv \eta$	$V_2 \equiv P_w$, $V_4 \equiv afa$, $V_{12} \equiv cv$, $V_{25} \equiv \dot{m}_a$	Belonio [29]

Table 1: Design and Optimization Input Data

Results and Discussion

The results are presented in tables and figures to support the discussions. Thus, the discussion of results are to be aided by Tables 1 and 2, Figures. 2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18 and 19. Figure 20 displays engineering working drawing for the optimized gasifier.

Results

The figures for the optimum design of both design functions and variables are portrayed in Figures. 2,3,4,5,6,7,8,9,10 ,11,12,13,14,15,16,17,18 and 19 according to the design functions in Table 1, which contains design and optimization input data, while Table 2 comprises output of the optimum design of the gasifier. Figurer 20 is useful for the fabrication of the optimized gasifier.

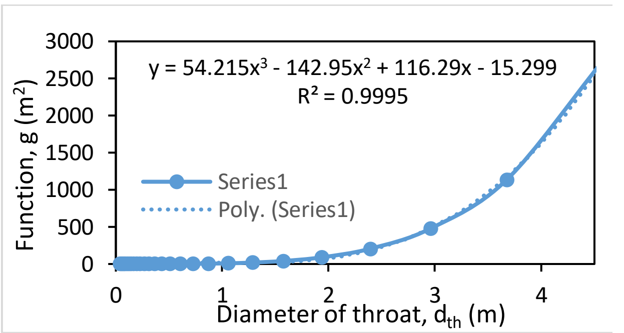

Figure 2: Optimum Diameter of Throat (d_{th}^*=0.0861 (m))

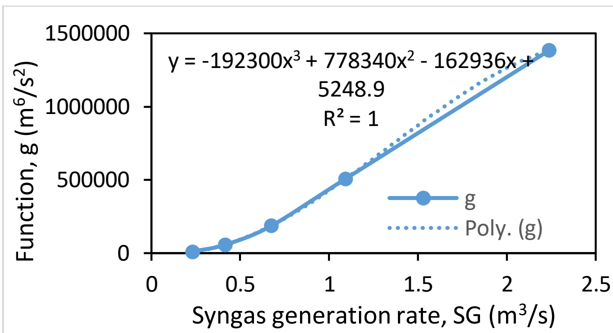

Figure 3: Optimum Syngas Generation Rate (SG^*=0.0048 (m^3/s))

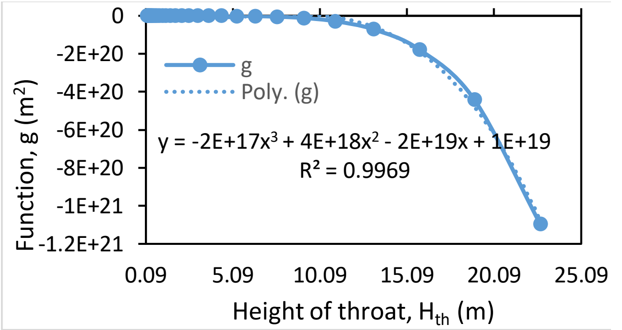

Figure 4: Optimum Height of Throat (H_{th}*=0.125 (m))

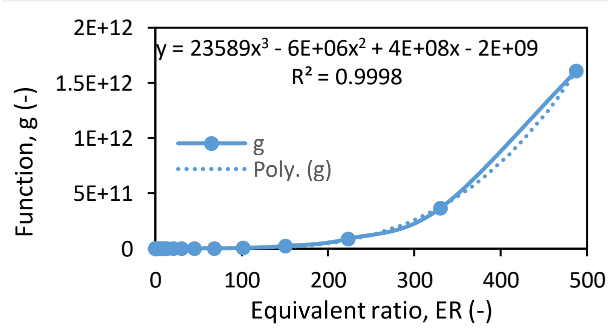

Figure 5: Optimum Equivalent Ratio (ER*=0.5699 (-))

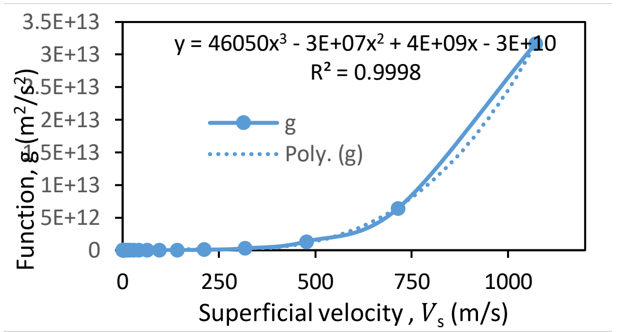

Figure 6: Optimum Superficial Velocity (V_s*=1.0280 (m/s))

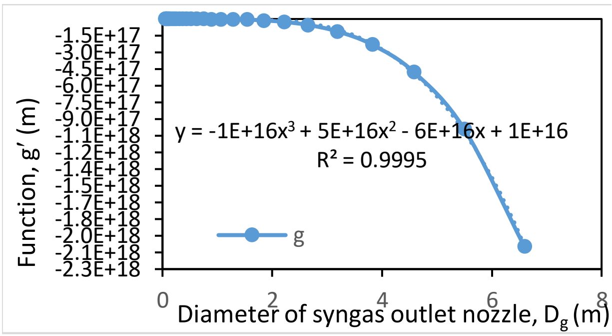

Figure 7: Optimum Diameter of Syngas Outlet Nozzle (D_g* 0.032 (m))

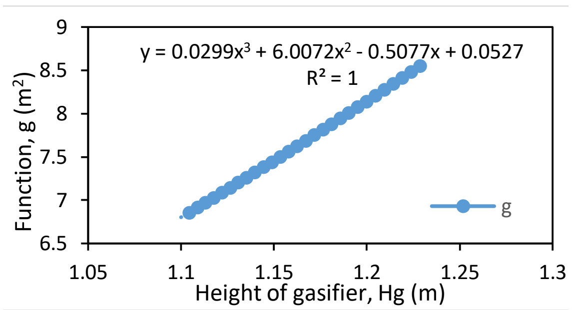

Figure 8: Optimum Height of Gasifier $(H_g^*$ ∄ $(m))$

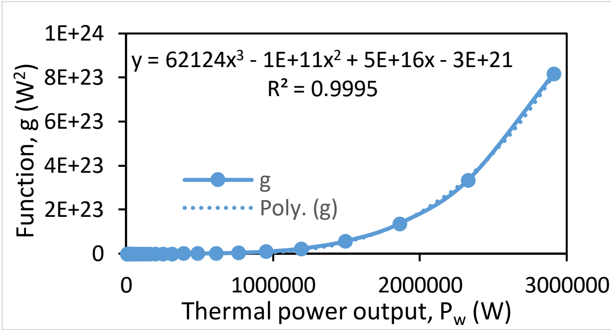

Figure 9: Optimum Thermal Power Output (P_w^*=4956.2408 (w))

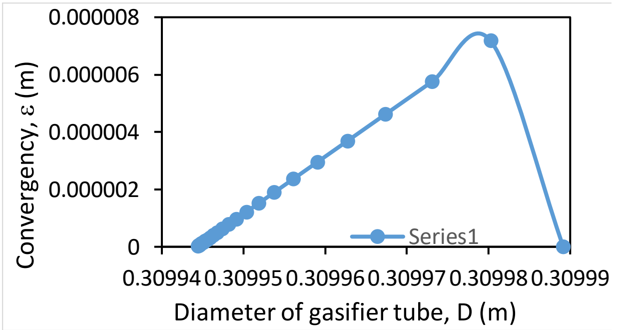

Figure 10: Optimum Diameter of Gasifier Tube (D^*=0.30997 (m))

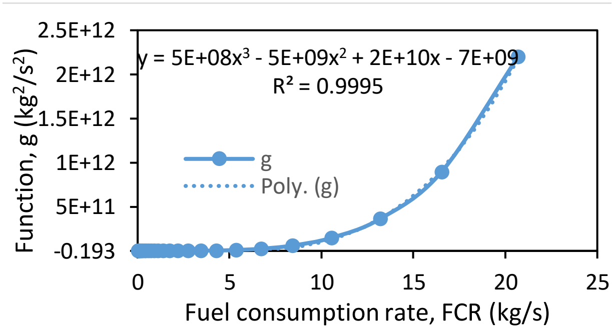

Figure 11: Optimum Fuel Consumption Rate (FCR^*=0.00025 (kg/s))

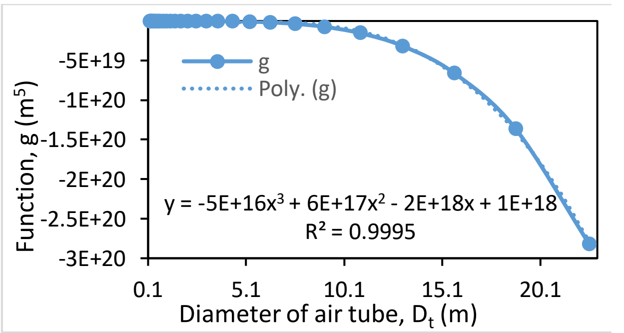

Figure 12: Optimum Diameter of Air Tube (D_t^*=0.0296 (m))

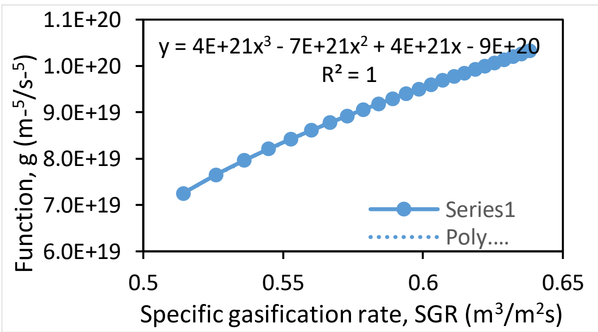

Figure 13: Optimum Specific Gasification Rate (SGR^*=0.0083 (m^3/m^2 s))

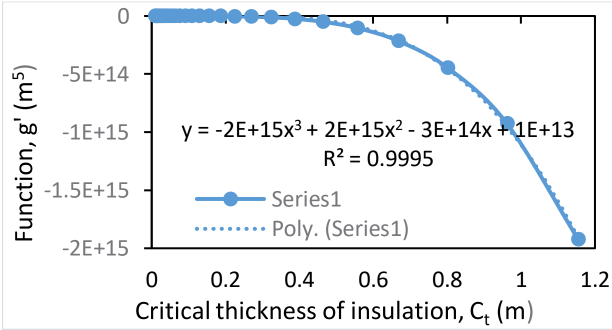

Figure 14: Optimum Critical Thickness of Insulation (C_t^*=0.0073 (m^2))

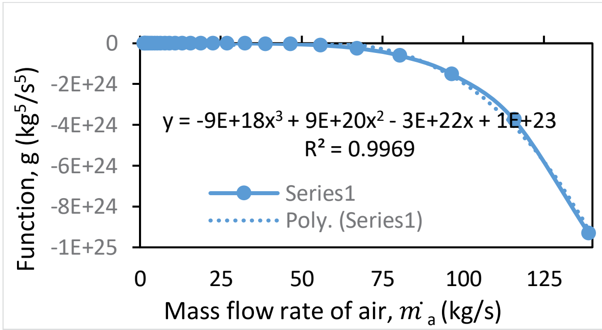

Figure 15: Optimum Mass Flow Rate of Air ($\dot{m}_a^*$= 0.4167 (kg/s))

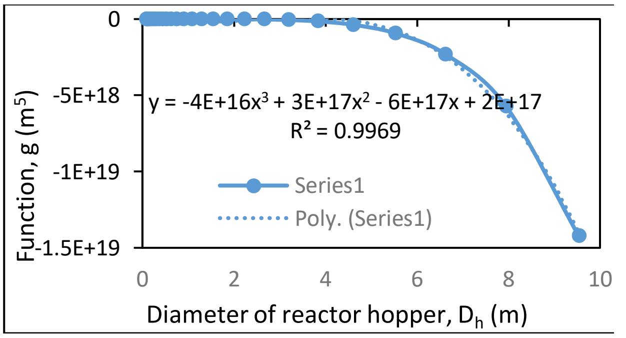

Figure 16: Optimum diameter of reactor hopper (D_h^*=0.0452 (m))

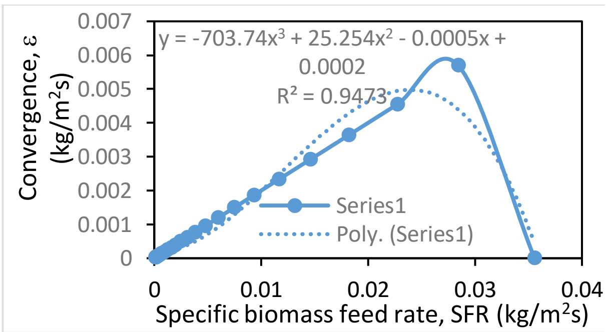

Figure 17: Optimum Specific Biomass Feed Rate ($SFR*$=0.0239 (kg/m^2 s))

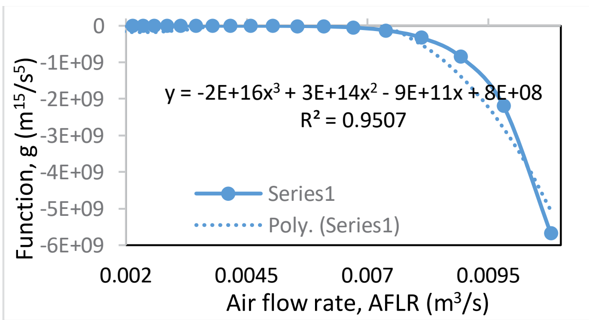

Figure 18: Optimum Air Flow Rate ($AFLR*$=0.00010 (m^3/s))

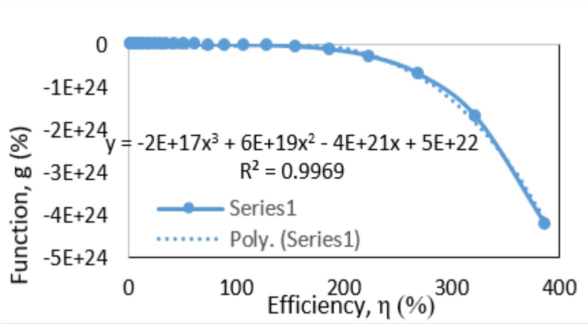

Figure 19: Optimum Efficiency (η*=52.8 (%))

Discussions

The discussion of the results covers the methodology, optimized variables and functions, parameterized variables, system design efficiency and application of results.

Optimization Techniques (Miso)

Generally, SISO outputs unoptimized design functions and variables according to the following studies [6-14]. The unoptimized results from SISO do not support optimum performance of biomass gasifier. Thus, the present study employed MISO scheme to achieve optimum design functions and variables created by SISO. The MISO scheme made use of design functions in Eqs. (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19a, 19b, 20, 21, 22, 23, 24) in conjunction with optimization flow chart in Figure. 1 and input data in Table 1 to obtain the optimum parameters in Table 2. According to the aforementioned references, the gasifier based on MISO is likely to perform better than the one based on SISO [6-14]. However, the theoretical performance evaluation can be carried out on testing of gasifier developed on SISO and MISO, which is beyond the scope of the design. In the light of unit synthesis, the following efficiencies 0.6 to 0.9 are recorded in the reviewed literature however, the system efficiency which focuses on unit operations was not captured by other studies, but the present study present optimum system efficiency that describes the unit operation or the physical equipment (gasifier) with value of 0.53 in Table 2. This result is thermally possible [8,11,19,21,26].

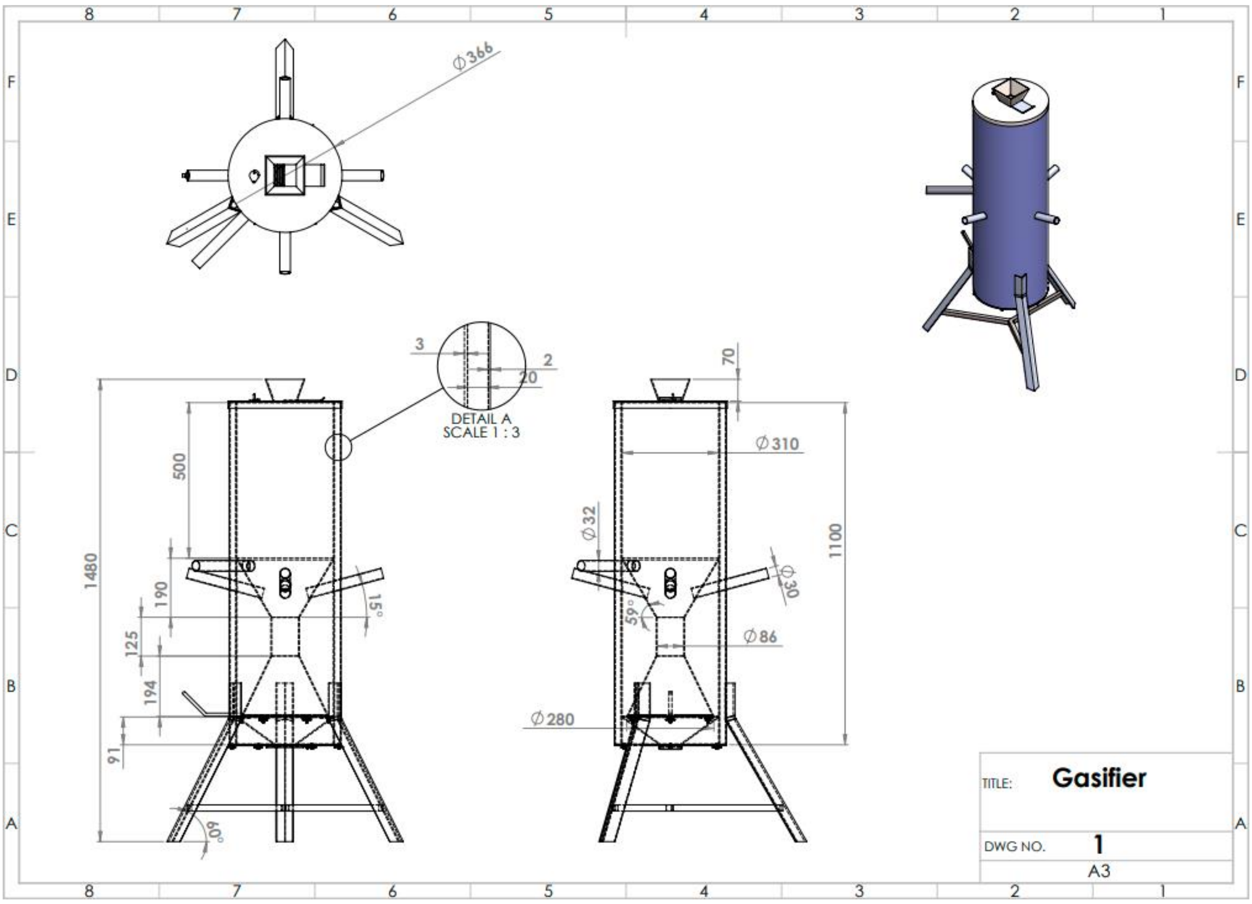

Figure 20: Gasifier Engineering Drawing Based on Optimum Design Values

Optimization of Design Variables and Functions

With the exception of height of gasifier, Hg in Figure. 8, other design functions and variables in Figs. 2,3,4,5,6,7,9,10,11,12,13,14,15,16,17,18 and 19 adhered to MISO optimization with characteristic nonlinear curves. Contrarily, Figure. 8 maintained a straight line for different coupled functions; linear coupled function (order equivalent to one) and nonlinear coupled function (order, n equivalent to $-5 \leq n \leq 5$). This implies that the gasifier height is not influenced by other design functions and variables. Therefore, it could be arbitrarily set by the designer as a degree of freedom, in which case it has influence on other design functions and variables but remain uninfluenced by other design functions and variables which implies that it is an independent variable and should not be considered as a design function according to Susastriawan et al. [30].

Parameterization of Variables

Parameterization becomes imminent where design function is function of one design variable. The optimum value of the design function is used to establish the optimum value of the corresponding design variable, typical example is throat diameter, which is defined by throat area and a constant in Eq. 1. Otherwise, parameterization of design variable becomes difficult with many design variables defining the design function. Hence, each design variable is transformed to design function and subjected to MISO algorithm to obtain the optimum value. This buttresses the fact that parameterization is a form of optimization [33,34]. However, the design function cannot be parameterized because it is a dependent variable.

System Design Efficiency

From Table 2, the optimum system design efficiency was found to be approximately 0.53 (53%) sequel to MISO optimization of the biomass gasifier. However, Wang et al. recorded optimum system efficiency of 27%. The difference in this results could be attributed to different optimization techniques as Wang et al. did not couple the design functions which the present work performed to achieve improved optimum system efficiency [27].

Application of the Results

Most gasifier designs are based on SISO scheme, hence, the final design output remains unoptimized. MISO will be vital in transforming the SISO designs to optimum designs in order to improve the performance of gasifier and other related thermal equipment as supported by the following studies [6-8].

Also, Figure. 20 will be useful for easy fabrication of the optimum downdraft gasifier for conversion of potential wood biomass, farm residues and municipal solid waste to syngas for combined heat and power applications.

S#	Symbol	Model of design function	R^2	Derivative of design function	Optimum Design	Scaled optimum design (80)	Selected optimum design
1.	$d_{th}(m)$	$Fig.2$	0.9994	]	$\{6.8895, 2.5712\}_{min}$	$\{0.0861, 0.0321\}_{min}$	0.0861
2.	SG (m^3/s)	$Fig.3$	1.0000	$\frac{dg}{d(SG)} = -576900SG^2 + 1556680SG - 162936$	$\{9.5976, 0.3847\}_{min}$	$\{0.120, 0.0048\}_{min}$	0.0048
3.	H_{th} (m)	$Fig.4$	0.9969	$\frac{dg}{d(H_{th})} = -6.0\times10^{17}H_{th}^2 + 8.0\times10^{18}H_{th} - 2.0\times10^{19}$	$\begin{Bmatrix}10,\\3.3333\end{Bmatrix}_{min}$	$\begin{Bmatrix}0.125,\\0.0417\end{Bmatrix}_{min}$	0.125
4.	ER	$Fig.5$	0.9998	$\frac{dg}{d(ER)} = 70767ER^2 - 1.2\times10^7 ER + 4.0\times10^8$	$\{123.9796, 45.5910\}_{min}$	$\{1.5497, 0.5699\}_{min}$	0.5699
5.	V_s (m/s)	$Fig.6$	0.9998	$\frac{dg}{d(V_s)} = 138150V_s^2 - 6.0\times10^7 V_s + 4.0\times10^9$	$\{352.0714, 82.2391\}_{min}$	$\{4.4009, 1.0280\}_{min}$	1.0280
6.	D_g (m)	$Fig.7$	0.9995	$\frac{dg}{d(D_g)} = -3.0\times10^{16}D_g^2 + 1.0\times10^{17}D_g - 6.0\times10^{16}$	$\begin{Bmatrix}2.5486,\\0.7847\end{Bmatrix}_{min}$	$\begin{Bmatrix}0.0319,\\0.0098\end{Bmatrix}_{min}$	0.0319
7.	H_g (m)	$Fig.8$	1.0000	$\frac{dg}{d(H_g)} = 0.0897H_g^2 + 12.0144H_g - 0.5077$	$Unoptimized$	$Unoptimized$	$\nexists$
8.	P_w (W)	$Fig.9$	0.9995	$\frac{dg}{d(P_w)} = 186372P_w^2 - 2.0\times10^{11}P_w + 5.0\times10^{16}$	$\{676623.31, 396499.26\}_m$	$\begin{Bmatrix}8457.79,\\4956.24\end{Bmatrix}_{min}$	4956.24

9.	D (m)	$Fig.10$	0.9468	$\frac{dg}{d(D)} = 0 \quad at \quad D = 0.30997$		$\{0.30997, 0.30997\}_{min}$	0.30997
10.	FCR (kg/s)	$Fig.11$	0.9995	$\frac{dg}{d(FCR)} = 1.5\times10^{9} FCR^2 - 1.0\times10^{10} FCR + 2.0\times10^{10}$	$\{6.6466, 0.0201\}_{min}$	$\begin{Bmatrix} 0.0831, \\ 0.00025 \end{Bmatrix}_{min}$	0.00025
11	$D_t(m)$	$Fig.12$	0.9995	$\frac{dg}{d(D_t)} = -1.5\times10^{17} D_t^2 + 1.2\times10^{18} D_t - 2.0\times10^{18}$	$\{5.6330, 2.3670\}_{min}$	$\begin{Bmatrix} 0.0704, \\ 0.0296 \end{Bmatrix}_{min}$	0.0296
12	SGR (m^3/m^2s)	$Fig.13$	1.0000	$\frac{dg}{d(SGR)} = 1.2\times10^{22} SGR^2 - 1.4\times10^{22} SGR + 4.0\times10^{21}$	$\{0.6667, 0.5000\}_{min}$	$\begin{Bmatrix} 0.0083, \\ 0.0062 \end{Bmatrix}_{min}$	0.0083
13	C_t (m)	$Fig.14$	0.9995	$\frac{dg}{d(C_t)} = -6.0\times10^{15} C_t^2 + 4.0\times10^{15} C_t - 3.0\times10^{14}$	$\{0.5805, 0.0861\}_{min}$	$\begin{Bmatrix} 0.0073, \\ 0.0011 \end{Bmatrix}_{min}$	0.0073
14	m_a (kg/s)	$Fig.15$	0.9969	$\frac{dg}{d(\dot{m}_a)} = 2.7\times10^{19} \dot{m}_a^2 + 1.8\times10^{21} \dot{m}_a + 3.0\times10^{22}$	$\{33.3333, 33.3333\}_{min}$	$\begin{Bmatrix} 0.4167, \\ 0.4167 \end{Bmatrix}_{min}$	0.4167
15	D_h (m)	$Fig.16$	0.9969	$\frac{dg}{d(D_h)} = -1.2\times10^{17} D_h^2 + 6.0\times10^{17} D_h - 6.0\times10^{17}$	$\{3.6180, 1.3820\}_{min}$	$\begin{Bmatrix} 0.0452, \\ 0.0173 \end{Bmatrix}_{min}$	0.0452
16	SFR (kg/m^2s)	$Fig.17$	0.9473	$\frac{dg}{d(SFR)} = -2111.22 SFR^2 + 50.508 SFR - 0.0005$	$\{0.0239, 0.0000\}_{min}$	$\begin{Bmatrix} 0.0003, \\ 0.0000 \end{Bmatrix}_{min}$	0.0239
17	AFLR (m^3/s)	$Fig.18$	0.9507	$\frac{dg}{d(AFLR)} = -6.0\times10^{16} AFLR^2 + 6.0\times10^{14} AFLR - 9.0\times10^{11}$	$\{0.0082, 0.0018\}_{min}$	$\begin{Bmatrix} 0.00010, \\ 0.00002 \end{Bmatrix}_{min}$	0.00010
18	η (%)	$Fig.19$	0.9969	$\frac{dg}{d(\eta)} = -6.0\times10^{17} \eta^2 + 1.2\times10^{20} \eta - 4.0\times10^{21}$	$\{157.7350, 42.2650\}_{min}$	$\begin{Bmatrix} 1.9717, \\ 0.5283 \end{Bmatrix}_{min}$	52.83

Table 2: Optimum Design Output of the Gasifier

Conclusion

This study has successfully carried out design optimization and parameterization of a downdraft gasifier using a multiple input and single output (MISO) strategy, which entails the assembly and coupling of design functions and variables to obtain a single unconstrained objective function that is subjected to optimization and parameterization to establish optimum design functions and variables.

The system efficiency was found to be 52.8%, which supersedes the 27% established by Wang et al. using conventional optimization techniques [27]. In addition, optimum design functions and variables were established for the improvement of the gasifier.

The design is useful for achieving improved system performance through the conversion of biomass to syngas. The height of the gasifier defies the optimization strategy and should not be used as a dependent variable in the formulation of design functions, as commonly employed in SISO. It is obvious that the MISO design strategy has the capacity to improve unit operations and unit synthesis of downdraft gasifier and gasification.

Acknowledgements

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