

Integration of Solar dryer with a Hybrid system of Gasifier- Solid Oxide Fuel Cell/Gas Turbine: Performance Analysis

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Abstract

A novel approach is presented to reduce the moisture content of biomass by employing a solar dryer. The impact of decreasing moisture contents on the key parameters of the system is investigated. Also, the effect of air mass flux on drying rate of biomass is evaluated and discussed considering three alternative air mass flux rates as well as two different time periods for drying and discharging biomass, namely 15 and 30 minutes. Results demonstrate that by reducing the moisture of biomass, power output and efficiency of the hybrid system have been improved from 265 kW and 30% efficiency up to 295 kW and 57.6% respectively. The best efficiency performance of system is achieved by the 15 minutes drain time and air mass flux of $0.011 \text{ kgm}^{-2}\text{s}^{-1}$, while the best power generation of the system will be obtained by the 30 minutes drain time and air mass flux of $0.011 \text{ kgm}^{-2}\text{s}^{-1}$.

Keywords: Biomass, Gasifier, Solar dryer, SOFC-GT, Performance analysis

1. Introduction

Biomass has been considered a vital energy resource on the earth. Based on sustainable development approaches, not only has it significant potential to enhance energy supplies in the

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world also it has a vast potential to be applied as an effective alternative strategy for supplying fuel and power generation [1]. Solid Oxide Fuel Cell (SOFC) is one of the most promising technologies for power production due to its great efficiency compared to rival technologies and its environmentally friendly energy production aspect. For decades, one of the most popular ideas in energy systems integration in the literature was the idea of SOFC and Gas Turbine (GT) integration. These integrated systems have been widely examined for Combined Heat and Power (CHP) applications because of their higher efficiency [2-6]. Several researches have studied biomass integration into SOFC-GT systems [7-13] and a variety of other novel biomass gasification systems have been integrated with SOFCs systems [14-18]. In addition, performance evaluation of an integrated biomass gasifier and SOFC-GT system has been comprehensively studied in the literature [19-24]. The integration of SOFC-GT with a gasifier is modelled numerically [19] in order to investigate the effects of gas components such as H_2 , CH_4 and CO on the overall system's performance. The findings revealed that the concentration of H_2 has the most pivotal influence on both the power and efficiency of the system, followed by CH_4 then CO in the order of impact. Different gasification agents like air, oxygen and steam have been taken into consideration by Coplan et al., [21] and Shayan et al., [23]. The results of both studies show that employing steam as gasification agent will improve overall performance of the integrated system significantly. A small-scale integration of a gasifier with SOFC-MGT have been studied by Perna et al., [25] where the effect of some influential operating parameters like Micro Gas Turbine (MGT) pressure ratio and the steam to carbon ratio have been examined to achieve the best electrical and thermal power generation of the system. The Results show that the best performances of the system will be obtained by the MGT pressure ratio of 4.5 and the steam to carbon ratio of 0. At the mentioned operation conditions, the corresponding electric power generation is 262 kW

while the thermal power is 405 kW. A variety of operating conditions impact, such as the effect of H_2 utilization and moisture content in biomass on the gasifier -SOFC system's performance have been analyzed by Campitelli et al., [26]. Also, the effects of some influential parameters such as equivalence ratio and mass flow rate of dry biomass as well as its moisture content on the overall performance of an integrated SOFC-MGT system have been investigated by Junxi Jia et al.,[27].

According to recent studies, one of the key factors affecting the performance of biomass integrated system is the moisture component in biomass. High moisture content in the biomass gasification of SOFC-GT is not desirable and will have negative effects on the system performance. Therefore, the moisture content has to be reduced to a certain level before biomass enters gasifier. As discussed earlier, this energy cannot be retrieved from the system [28]. One of the current methods of reducing the moisture of biomass is using fossil fuels dryer, where the moisture content in biomass is reduced by burning fossil fuel, that will pose some significant environmental issues. To the best of authors knowledge, there is no previous research using a semi-continues solar dryer to later the moisture content of biomass. Therefore, to provide solution to this problem, the present study purposes a new idea to reduce the moisture of input biomass by employing the active mixed semi-continuous solar dryer. After this dry biomass is logged into the gasifier system, the synthesis gas generated by the gasifier enters the SOFC-GT hybrid system that generates electricity. Furthermore, a parameter study regarding the initial and final moisture content will be obtained from the products.

The main objective of this study is to investigate the moisture influence on the temperature of gasifier and fuel cell, fuel calorific value, the output power of the system and the impact of using the solar dryer on both efficiency and output power of the hybrid system. Significance and advantage of the present work is employing environmentally friendly approach to enhance a totally

renewable energy hybrid system overall performance to avoid detrimental effects of burning fossil fuels for drying biomass. Another practical advantage of this method is it can be used in rural areas where plenty of biomass resources are available. In order to make renewable energy technologies more competitive in the current energy market, the proposed system could have significant privileges due to using conventional power generators along with alternative fuel resources.

2. Material and methods

2.1. System description

The proposed system is divided into three subsystems in which the core technology is a biomass gasification plant. A down-draft gasifier is studied with steam as the gasification agent. The second unit is a SOFC-GT hybrid system which is fed by the syngas generated by the gasifier. Besides, the proposed plant includes a “Semi-Continuous Solar Dryer” to reduce the moisture content of biomass to an acceptable level before entering the gasifier. Other auxiliary pieces of equipment like a pump, Heat Recovery Steam Generator (HRSG) and a heat exchanger are used to enhance the system's performance. The schematic diagram of the proposed plant is depicted in Figure 1. Firstly, wet biomass enters the solar dryer and its moisture content will be reduced, then dried biomass is introduced to the gasification plant to be turned into syngas. Presumably, the syngas produced by down-draft gasifier contains some contaminants such as tar, sulfur, etc. which has harmful technical effects when used in SOFC module. Consequently, a gas filtration system is facilitated to separate impurities and supply clean syngas to the SOFC. The purified combustible raw syngas will be introduced to the anode side of the SOFC, while the compressed air initially heated by the gas turbine exhausts will enter the cathode side of the SOFC where electricity will be generated by means of some electrochemical reactions. The off-fuel and the off-air which came from the anode and cathode sides of the SOFC are introduced to a combustor to be burnt to acquire

additional electric power by expanding through the GT. Eventually, the stream of burned gas supplies heat to the HRSG to produce steam and then let to the environment.

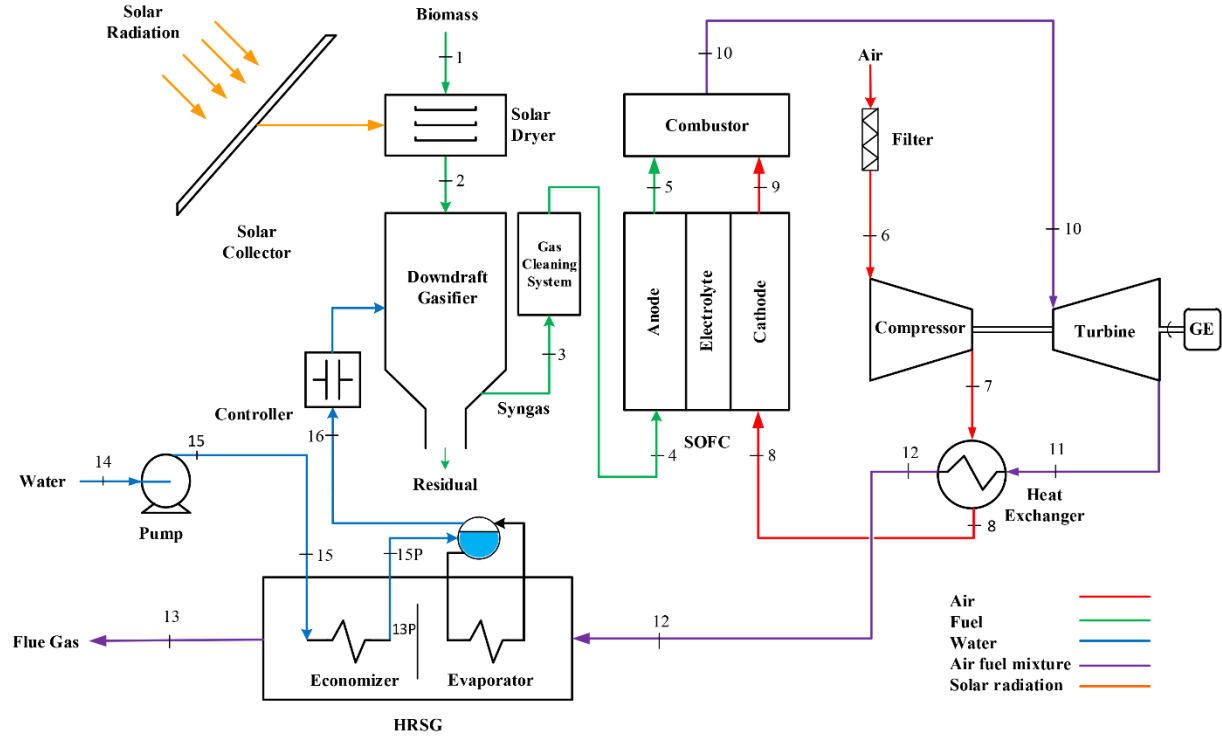


Figure 1. The Schematic block diagram of plant.

2.2. Numerical modeling

The simulation model is described here to determine the key components of the designed layout. A comprehensive model was developed in MATLAB to accurately evaluate the system's performance under a variety of operating conditions.

2.2.1 Solar dryer

The solar dryer used in our simulation was designed and built by the department of agricultural engineering of Shiraz University [29]. This dryer is a cross flow and an active mixed-mode type that works semi-continuously and is able to adapt to the workload. The Solar dryer equations is presented in Table 1. [29]

Table 1. The solar dryer equations [29]

$q_c = \dot{m}c_p(T_2 - T_1)$	(1)
$\eta_c = \frac{q_c}{G_T}$	(2)
$q_{loss} = \dot{m}C_p(T_3 - T_2)$	(3)
$W = 0.622 \frac{\phi P_{vs}}{P - \phi P_{vs}}$	(4)
$h = 1006.9t + W[2512131.0 + 1552.4t]$	(5)
$\eta_{drying} = \frac{(h_1 - h_2)}{h_1}$	(6)
$q_{drying} = \eta_{drying}(A_c q_c + q_{heater} - q_{loss})$	(7)
$\eta_{net} = \frac{q_{drying}}{(q_c + q_{fan} + q_{heater})}$	(8)

More details about the calculation process and solar dryer specifications may be found in [29].

2.2.2 Down- draft gasifier

Numerical modeling is applied to simulate the processes of a down-draft gasifier. A simple structure of a downdraft gasifier is illustrated in Figure 2. As shown, the gasifier consists of two principal parts, including the pyrolysis-oxidation zone and the reduction zone, where the pyrolysis and oxidation reactions will take place in succession followed by the reduction reactions [27].

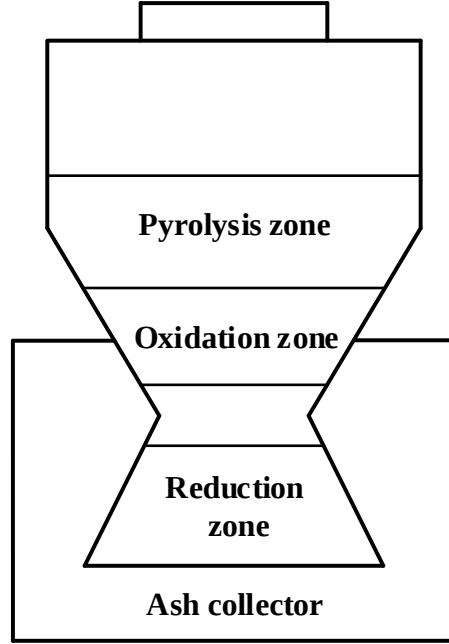


Figure 2. Schematic diagram of a down-draft gasifier [27]

The down-draft gasifier equations are listed in Table 2. To determine the pyrolysis-oxidation zone reactions, the global reaction formula is written as equation (9). Further, the impact of biomass moisture content (MC) as well as supplied air to the gasification process, are evaluated by equations (10,11) [27]. Then, two equilibrium reactions named, methane formation and the shift reaction in the pyrolysis-oxidant zone (12,13) are employed to solve the equations [27]. Equilibrium constants for these reactions are presented by equations (14) and (15), respectively also, the energy balance can be obtained by equation (16) [27]. The pyro-oxidation zone calculation results will be introduced as input parameters to the reduction zone. The reduction reactions can be written as equations (17-20) while the volumetric reaction rate of each chemical reaction can be written as equations (21-24) [27]. Furthermore, the Cold Gas Efficiency (CGE) metric is used to assess the progress of gasification defined as equation (25) [30].

Table 2: The down-draft gasifier [27].

$\text{CH}_a\text{O}_b\text{N}_c + w\text{H}_2\text{O} + m(\text{O}_2 + 3.76\text{N}_2)$	
$\rightarrow x_1\text{H}_2 + x_2\text{CO} + x_3\text{CO}_2 + x_4\text{H}_2\text{O} + x_5\text{CH}_4 + x_6\text{N}_2 + x_7\text{C}$	(9)
$\text{MC} = \frac{M_w}{M_{\text{Bio}} + M_w} = \frac{18w}{(12 + a + 16b + 14p) + 18w}$	(10)
$\text{ER} = \frac{\text{Air}_{\text{Actual}}}{\text{Air}_{\text{Stoichiometric}}} = \frac{m}{(1 + 0.25a - 0.5b)}$	(11)
$\text{C} + 2\text{H}_2 \leftrightarrow \text{CH}_4$	(12)
$\text{CO} + \text{H}_2\text{O} \leftrightarrow \text{H}_2 + \text{CO}_2$	(13)
$K_1 = \frac{x_5 n_T}{x_1^2 P_0}$	(14)
$K_2 = \frac{x_1 x_3}{x_2 x_4}$	(15)
$\text{H}_{\text{Biomass}} + w\text{H}_{\text{H}_2\text{O}} + m(\text{H}_{\text{O}_2} + 3.76\text{H}_{\text{N}_2})$	
$= x_1\text{H}_{\text{H}_2} + x_2\text{H}_{\text{CO}} + x_3\text{H}_{\text{CO}_2} + x_4\text{H}_{\text{H}_2\text{O}} + x_5\text{H}_{\text{CH}_4} + x_6\text{H}_{\text{N}_2} + x_7\text{H}_{\text{C}}$	(16)
$\text{R}_1: \text{C} + \text{CO}_2 \leftrightarrow 2\text{CO}$	(17)
$\text{R}_2: \text{C} + \text{H}_2\text{O} \leftrightarrow \text{CO} + \text{H}_2$	(18)
$\text{R}_3: \text{C} + 2\text{H}_2 \leftrightarrow \text{CH}_4$	(19)
$\text{R}_4: \text{CH}_4 + \text{H}_2\text{O} \leftrightarrow 3\text{H}_2 + \text{CO}$	(20)
$r_{\text{R}_1} = C_{\text{RF}} A_{\text{R}_1} \exp\left(\frac{-E_{\text{R}_1}}{R_m T}\right) \left(y_{\text{CO}_2} - \frac{y_{\text{CO}_2}^2}{k_{\text{R}_1}}\right)$	(21)
$r_{\text{R}_2} = C_{\text{RF}} A_{\text{R}_2} \exp\left(\frac{-E_{\text{R}_2}}{R_m T}\right) \left(y_{\text{H}_2\text{O}} - \frac{y_{\text{H}_2} y_{\text{CO}}}{k_{\text{R}_2}}\right)$	(22)
$r_{\text{R}_3} = C_{\text{RF}} A_{\text{R}_3} \exp\left(\frac{-E_{\text{R}_3}}{R_m T}\right) \left(y_{\text{H}_2}^2 - \frac{y_{\text{CH}_4}}{k_{\text{R}_3}}\right)$	(23)
$r_{\text{R}_4} = C_{\text{RF}} A_{\text{R}_4} \exp\left(\frac{-E_{\text{R}_4}}{R_m T}\right) \left(y_{\text{H}_2\text{O}}^2 y_{\text{CH}_4} - \frac{y_{\text{CO}} y_{\text{H}_2}^3}{k_{\text{R}_4}}\right)$	(24)
$\text{CGE} = \frac{\text{GY}_f \times \text{HHV}_{\text{PG}}}{\text{HHV}_f \times \text{Heat}_{\text{aer}}}$	(25)

Where the unknown parameters $x_1, x_2, x_3, x_{14}, x_5, x_6, x_7$ and T (the reaction temperature) will be determined. By using energy and mass balance equations and bisection approach, above equations

and reaction temperature will be calculated. More details about the calculation process as well as the thermodynamic properties values may be found in [27, 28].

2.2.3 SOFC numerical model

To investigate the SOFC performance, it is crucial to consider a model that is capable of predicting the performance based on its operating condition. The schematic diagram of the electrochemical processes occurring in a planar SOFC system is illustrated in Figure 3.

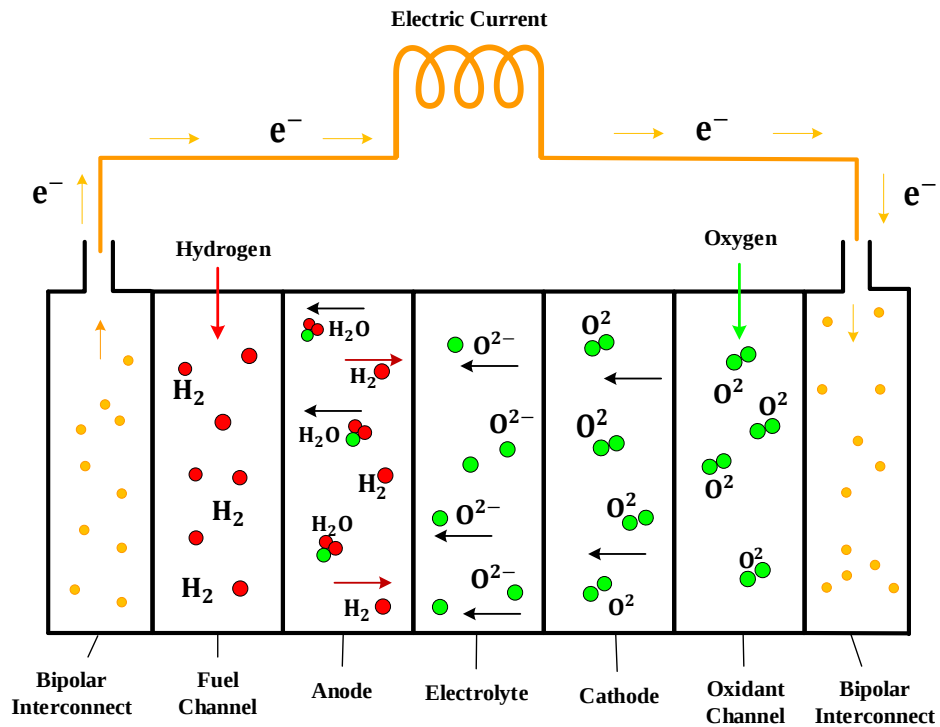


Figure 3. The Schematic of a planar SOFC system.

The SOFC electrochemical equations are presented in Tables 3 - 6. The operating cell voltage is calculated by equation (26). Table 3. Lists the voltage equations [31].

Table3. Voltage equations [31]

$$V_{\text{Cell}} = V_{\text{OCV}} - (\sum_j \eta_{\text{ohm},j} + \eta_{\text{conc},3} + \eta_{\text{conc},5} + \eta_{\text{act},3} + \eta_{\text{act},5}), \quad j = 1, 3, 4, 5 \quad (26)$$

$$V_{OCV} = -\frac{1}{2F} \left(H_{H_2O} - H_{H_2} - \frac{1}{2} H_{2O} \right) + \frac{T}{2F} \left(S_{H_2O}^0 - S_{H_2}^0 - \frac{1}{2} S_{O_2}^0 \right) + \frac{RT}{2F} \ln \left(\frac{P_{H_2O}}{P_{H_2}(P_{O_2})^{1/2}} \right) \quad (27)$$

The materials resistance, involved interconnector anode, cathode, electrolyte, and the ohmic losses will be calculated from equations (28-32) listed in Table 4 [31].

Table 4. Ohmic losses equations [31].

$$\eta_{Ohm,j} = I\beta_j, \quad j = 1, 4 \quad (28)$$

$$\eta_{Ohm,j} = \frac{I(A_{j,opt} - L_y L_z) L_{j,opt}}{2A_{j,opt} L_y L_z (1 - \varphi_j) \sigma_4} + \frac{I(L_j - L_{j,opt})}{L_y L_z (1 - 1.8\varphi_j) \sigma_i} \quad j = 3, 5 \quad (29)$$

$$\beta_1 = \frac{L_1}{L_y L_z \sigma_1} + \frac{L_2}{(1 + n_{CH}) L_t L_y \sigma_1} + \frac{L_6}{(1 + n_{CH}) L_t L_z \sigma_1} \quad (30)$$

$$\beta_4 = \frac{L_4}{L_y L_z \sigma_4} \quad (31)$$

$$A_{j,opt} = \left(1 + \frac{2L_{j,opt}\varphi_j}{D_{P,j}} \right) L_y L_z \quad (32)$$

Following the diffusion losses will be determined using equations listed in Table 5 [31].

Table 5. Diffusion losses equations [31].

$$D_{P,j} = \frac{D_{w,j}\varphi_j}{(1 - \varphi_j)} \quad (33)$$

$$P_{H_2O,TPB} = p_f x_{H_2O} + \frac{RT \psi_3}{2FD_3 \psi_3} \frac{L_3 I}{L_y L_z} \quad (34)$$

$$P_{H_2,TPB} = p_f x_{H_2} - \frac{RT \psi_3}{2FD_3 \psi_3} \frac{L_3 I}{L_y L_z} \quad (35)$$

$$P_{O_2,TPB} = p_{air} - (p_{air} - x_{O_2} p_{air}) \exp \left(\frac{RT \psi_5 L_5 I}{4FD_5 \psi_5 p_{air} L_y L_z} \right) \quad (36)$$

$$D_3 = \frac{1.43 \times 10^{-7} T^{1.75} (M_{H_2} + M_{H_2O})^{1/2}}{P_f (2M_{H_2} + M_{H_2O})^{1/2} \left(v_{H_2}^{1/3} + v_{H_2O}^{1/3} \right)^2} \quad (37)$$

$$D_5 = \frac{1.43 \times 10^{-7} T^{1.75} (M_{O_2} + M_{N_2})^{1/2}}{P_{air} (2M_{O_2} + M_{N_2})^{1/2} \left(v_{O_2}^{1/3} + v_{N_2}^{1/3} \right)^2} \quad (38)$$

$$\eta_{diff,c} = \frac{RT}{4F} \ln \left(\frac{p_{O_2}}{p_{O_2,TPB}} \right) \quad (39)$$

$$\eta_{diff,a} = \frac{RT}{4F} \ln \left(\frac{p_{H_2} p_{H_2O,TPB}}{p_{H_2,TPB} p_{H_2O}} \right) \quad (40)$$

Later the activation loss, which is related to the irreversibility of the electrochemical reaction, can be examined by the equations listed in Table 6.

Table 6. Activation losses equations [31]

$$i = i_{o,j} \left[\exp \left(\frac{\alpha n F}{RT} \eta_{act,j} \right) - \exp \left(- \frac{(1 - \alpha) n F}{RT} \eta_{act,j} \right) \right], j = 3, 5 \quad (41)$$

$$\eta_{act,j} = \frac{RT}{\alpha n F} \sinh^{-1} \left(\frac{i}{i_{o,j}} \right) \quad (42)$$

$$i_{o,j} = \frac{RT}{nF} \delta_j \exp \left(- \frac{E_j}{RT} \right), j = 3, 5 \quad (43)$$

The electrical power generated by the SOFC can be calculated by (44,45) as follow [32]:

$$\dot{W}_{SOFC} = N \cdot V_{Cell} \cdot j \cdot A_C \quad (44)$$

$$\dot{W}_{SOFC,net} = \dot{W}_{SOFC} \cdot \eta_{inv} \quad (45)$$

Where η_{inv} is the inverter efficiency that is considered to be 0.98 [32]. The heat generated and the overall efficiency of SOFC can be determined as follows [32]

$$\dot{Q}_{SOFC} = (\dot{m}_f \cdot U_f \cdot LHV) \quad (46)$$

$$\eta_{HS} = \frac{\dot{W}_{net}}{\dot{Q}_{tot}} \quad (47)$$

Mass balance of SOFC considering input and output flows may be written as [32]:

$$\sum \dot{m}_i = \sum \dot{m}_e \quad (48)$$

$$\dot{m}_4 + \dot{m}_8 = \dot{m}_5 + \dot{m}_9 = \dot{m}_8 + (\dot{m}_4 U_f) + \dot{m}_4(1 - U_f) \quad (49)$$

Where, $\dot{m}_4$ is the fuel mass rate injected to the SOFC and $\dot{m}_8$ is the air mass rate injected to SOFC.

Alternatively, applying the first law of thermodynamic equation (49) can be rewritten as [32]:

$$\dot{m}_8 h_8 + (\dot{m}_4 U_f) \text{LHV} + \dot{m}_4(1 - U_f) h_4 - \dot{m}_5 h_5 - \dot{m}_9 h_9 = 0 \quad (50)$$

where LHV stands for the lower heating value of biomass. It should be noted that all products are considered to be adiabatic.

2.2.4. Other auxiliary equipment

The proposed design consists of other auxiliary pieces of equipment including Air Compressor, Gas turbine, Combustion chamber, Heat exchanger and Heat recovery steam generator (HRSG).

The governing equations on them are listed in Table 7 [32].

Table 7. Other auxiliary pieces equipment equations [29].

$$\eta_{AC} = \frac{W_s}{W_a} = \frac{\bar{h}_{7s} - \bar{h}_6}{\bar{h}_7 - \bar{h}_6} \quad (51)$$

$$\frac{T_{7s}}{T_6} = \left(\frac{P_7}{P_6} \right)^{\gamma-1/\gamma} \quad (52)$$

$$\dot{W}_{AC} = \dot{m}_6(\bar{h}_7 - \bar{h}_6) \quad (53)$$

$$\eta_{tis} = \frac{W_a}{W_s} = \frac{\bar{h}_{10} - \bar{h}_{11}}{\bar{h}_{10} - \bar{h}_{11s}} \quad (54)$$

$$P_{rt} = \frac{P_{10}}{P_{11}} \quad (55)$$

$$\dot{W}_T = \sum_i (\dot{m}_{10} \bar{h}_{10})_{in} - \sum_i (\dot{m}_{11} \bar{h}_{11})_{out} \quad (56)$$

$$\dot{W}_{GT} = (\dot{W}_T - \dot{W}_{AC}) \mu_m \cdot \mu_g \quad (57)$$

$$\sum_{i=1}^7 \dot{m}_i^{in} \left(\Delta H_f^0 + \int_{298}^{T_{in}} C_p dT \right) = \sum_{i=1}^4 \dot{m}_i^{out} \left(\Delta H_f^0 + \int_{298}^{T_{out}} C_p dT \right) \quad (58)$$

$$\varepsilon_{APH} = \frac{T_{12} - T_8}{T_{11} - T_7} \quad (59)$$

$$\dot{m}_7(h_{12} - h_7) = \dot{m}_{11}(h_{11} - h_{12})\varepsilon_{APH} \quad (60)$$

$$\dot{m}_g = \dot{m}_a + \dot{m}_f \quad (61)$$

$$\dot{m}_s(h_{16} - h_{15}) = \dot{m}_g(h_{12} - h_{13}) \quad (62)$$

$$\dot{m}_s(h_{16} - h_{15P}) = \dot{m}_g(h_{12} - h_{13P}) \quad (63)$$

$$P_0 = P_{12}(1 - \Delta P_{HRSG}) \quad (64)$$

Further $\dot{W}_T$ can be determined by equation (56) following the $\dot{W}_{GT}$ can be obtained by (57) [32]. Where μ_m is assumed 0.80 and μ_g is assumed 0.98 [33]. Also, the energy balance of the combustor is expressed by equation (58) [32]. The isentropic efficiency of the air preheater can be defined by equation (59) followed by the energy conservation that can be calculated by equation (60), where ε_{APH} is the isentropic efficiency of air preheater [34]. The HRSG is employed to recover energy from the exhausts gas of turbine as well as generating some auxiliary steam to be utilized in an internal reformer where water is pumped to the HRSG. The steam flow rate generated by the HRSG, $\dot{m}_s$, can be determined by considering the equations (61-64) simultaneously [34].

2.2.5. Power and efficiency

The energy balance for the proposed hybrid system can be written as [32, 34]:

$$\dot{m}_1 h_1 + \dot{m}_{16} h_{16} + \dot{m}_4 U_f LHV + \dot{Q}_{CC} - \dot{m}_{17} h_{17} - \dot{Q}_{Loss} - \dot{W}_P - \dot{W}_{GT} = 0 \quad (65)$$

The total energy efficiency and net power output of the proposed hybrid system including the SOFC and GT hybrid cycle is determined as [32, 34]

$$\dot{W}_{net} = (\dot{W}_{SOFC} + \dot{W}_{GT} - \dot{W}_{WP}) \quad (66)$$

$$\dot{Q}_{tot} = (\dot{m}_{biomass} * U_f * LHV) \quad (67)$$

$$\eta_{HS} = \frac{\dot{W}_{net}}{\dot{Q}_{tot}} \quad (68)$$

2.3 Simulation and validation

The model input data of the considered integrated down-draft gasifier SOFC/GT system are selected from [27, 29-31, 33]. Input parameters for simulation of the solar dryer is derived from [27]. The values of the operation parameters in modelling of the down-draft gasifier are selected from [29]. The properties and constant values used in the planar SOFC model may be found in [31, 33]

Table 8: Gas composition comparison by experimental results for moisture content 10% [27].

Gas Composition (%)	Hydrogen	Carbon monoxide	Carbon dioxide	Methane
Present study	16.99	17.51	11.41	1.26
Experimental results	16.81	19.70	12.30	1.90

Our results are in a reasonable agreement with counterparts in literature.

3. Solution methodology

In this work, we have used a solution methodology that conducts the performance analysis of operation conditions. The main objective of proposed methodology is providing the operation solutions based on technical model for engineering applications. The technical proposed model will be solved in six consecutive steps by employing all required equations in a structured way as illustrated in Figure. 3. To solve the technical model, constant parameters are selected initially followed by modelling solar dryer, down-draft gasifier, SOFC, GT, HRSG, and energy balance. Later, power and efficiency will be calculated as the dependent variables.

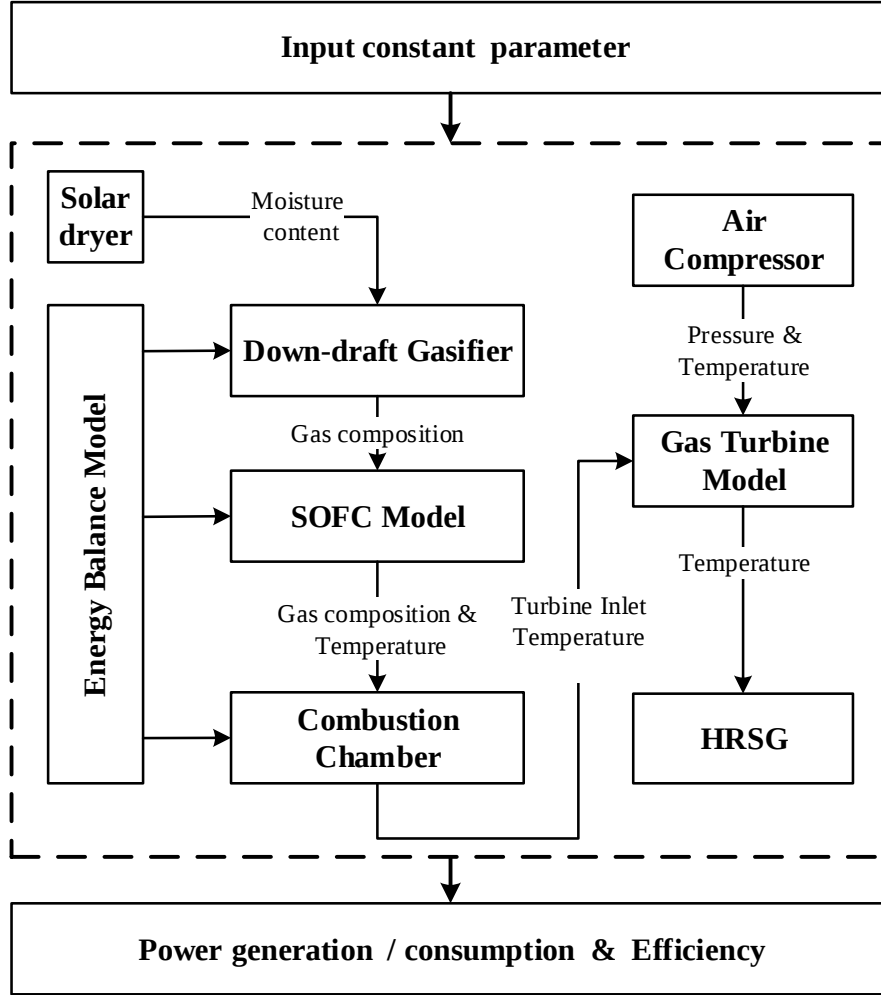


Figure 4. The model structure for integrated Gasifier SOFC/GT system.

4. Results and discussion

In this section, the impact of decreasing moisture content by employing solar dryer on different kinds of parameters have been studied. The parameters include syngas composition, gasifier temperature, SOFC temperature, fuel calorific value, efficiency and power output of the hybrid system. The effect of moisture content on gas composition is given in Figure 5. The gas composition is highly dependent to the moisture content such that as moisture content is increased from 0 % to 40 %, the molar fraction of generated gases will be affected significantly. It should be noted that although in practice achieving a 0% moisture content might be impossible, the objective of this study is to determine the maximum possible efficiency.

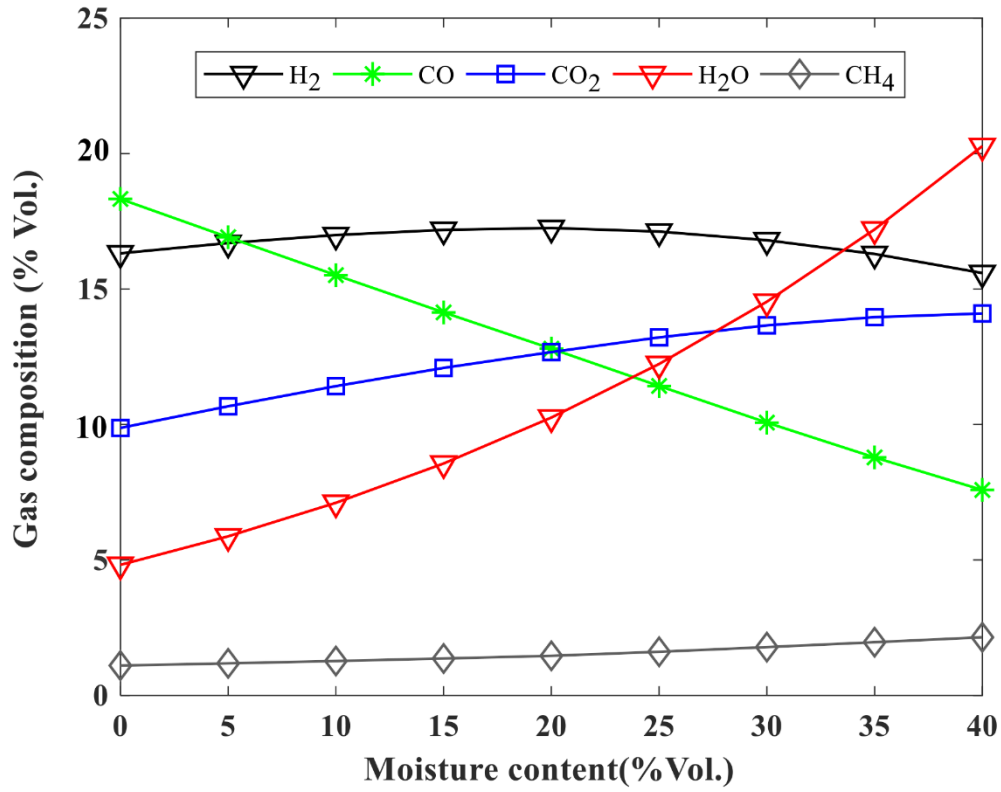


Figure 5: Gas composition versus Moisture Content

As shown in Figure 5. by increasing the biomass moisture amount, the mole fraction of H₂ gradually increased until 25% moisture and starts decreasing afterwards while the mole fraction of CO is decreased dramatically and linearly. It is noteworthy that as moisture content increased from 10% to 20%, the CO molar fraction experiences a 4% drop, i.e. from 0.16% to 0.12%, while at the same moisture, the H₂O molar fraction increased from 0.075% to 0.1%. Also, the CH₄ which consists a small fraction of produced gas undergoes a slight boost, like CO₂ with the same trend when the moisture content increases. Our findings on moisture content amount variation on syngas composition hint that although lower moisture content is favored to provide high-quality syngas,

maintaining the moisture content of about 20%- 25% is desirable to produce a better combustible syngas considering all syngas components.

In Figure 6. the variation of moisture content amount versus gasifier temperature is illustrated. It can be seen that by increasing moisture content the gasifier temperature declines significantly.

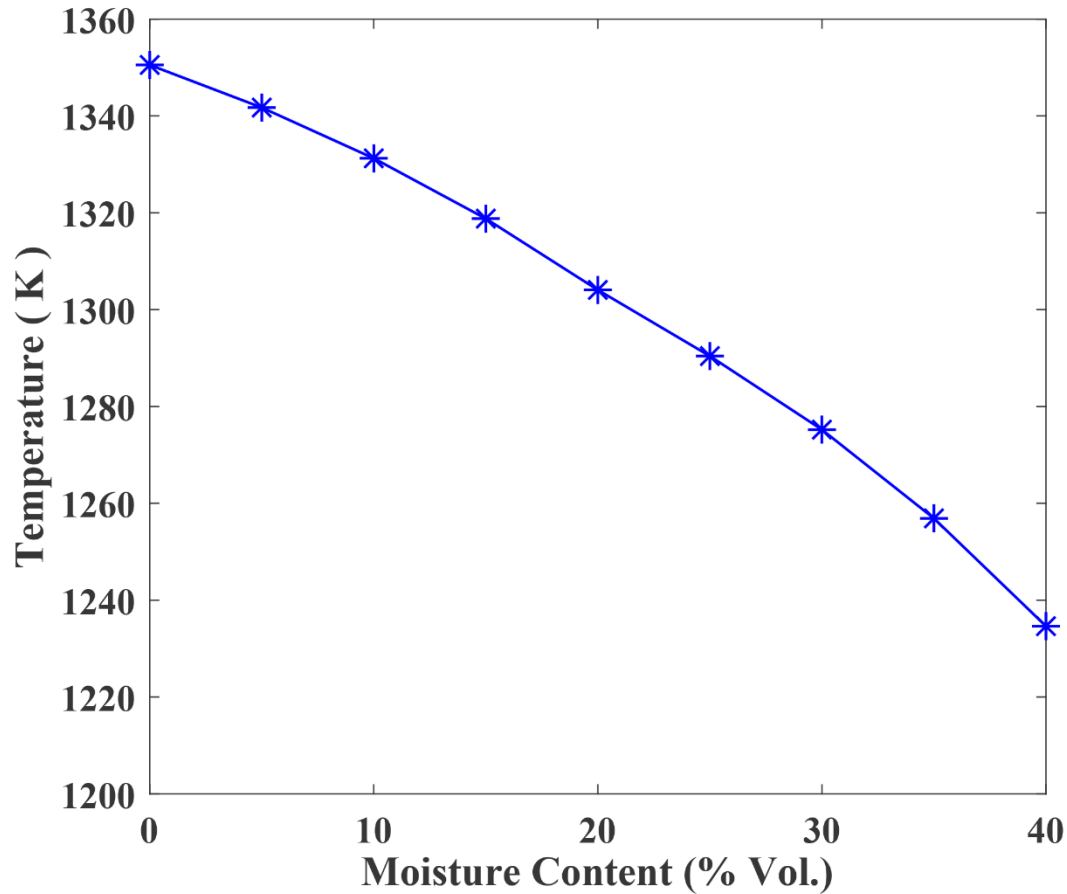


Figure 6. Temperature changes relative to moisture

It is illustrated that on average there is a temperature drop of approximately 30 K when moisture content increases every 10%. For example, when moisture content increases from 10% to 20% the correspond gasifier temperature drops from 1330 K to 1300 K.

It is confirmed that the temperature drops as the moisture content increases, in either case. This is mainly according to the fact that, by assuming constant inlet air, as biomass moisture content

increases, more heat is required to evaporate its moisture, hence the process equilibrium temperature is reduced.

In Figure 7. A parametric study is conducted to determine the effects of gasifier temperature on generated gas composition to assess the best working temperature of gasifier with the aim to achieve better syngas composition.

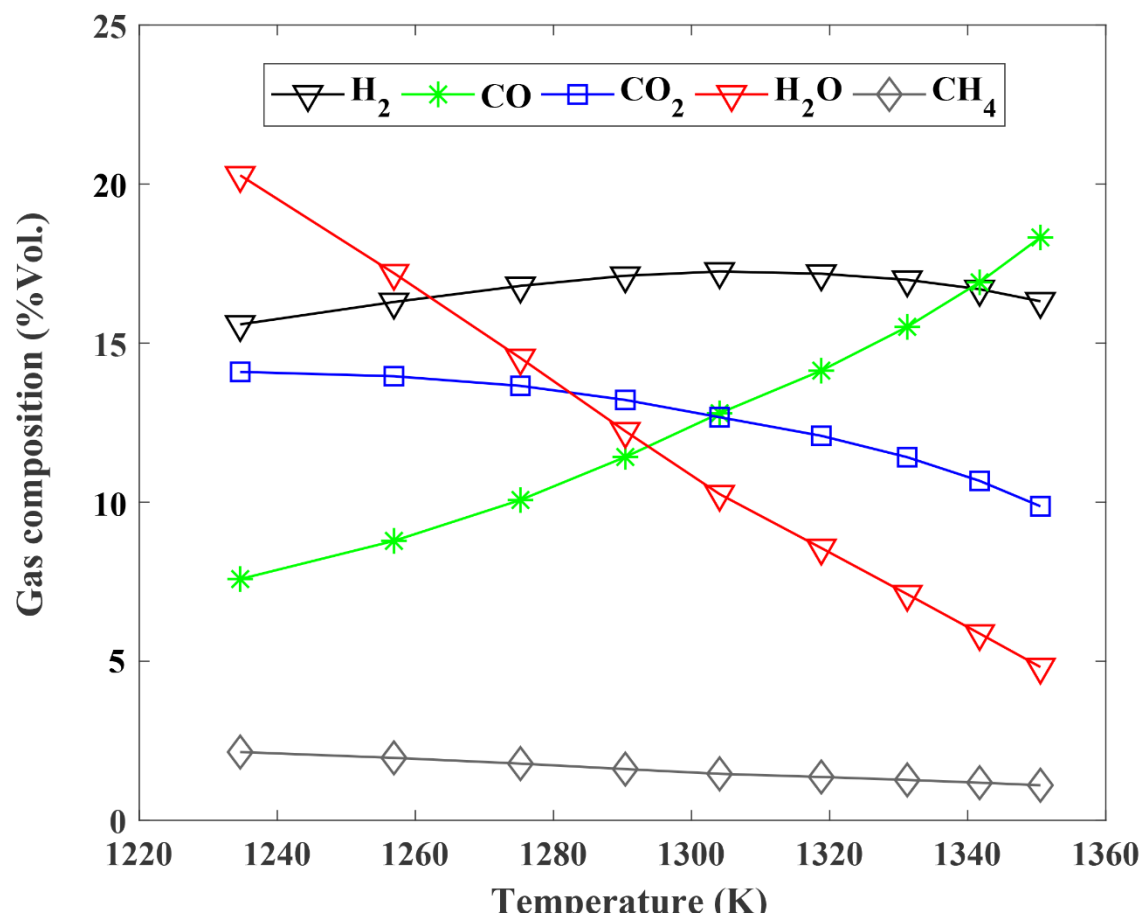


Figure 7: Gas composition versus Gasifier temperature

As expected, concentration of H₂O is highly correlated to gasifier working temperature where on average by every 10 K reduction in gasifier temperature, H₂O concentration in the generated gas will be decreased approximately 7%.

The molar fraction of CH_4 is considerably less than other species in the gas composition and this is mainly since most of carbon content is converted into CO . It is observed that by increasing temperature, the concentration of CH_4 and CO_2 decline while concentration of CO increases remarkably. It can be understood that the highest concentration of H_2 amount is achieved when gasifier working temperature lay between 1300 K to 1320 K. This operation condition happens when the hydrogen concentration in the syngas is about 18 %.

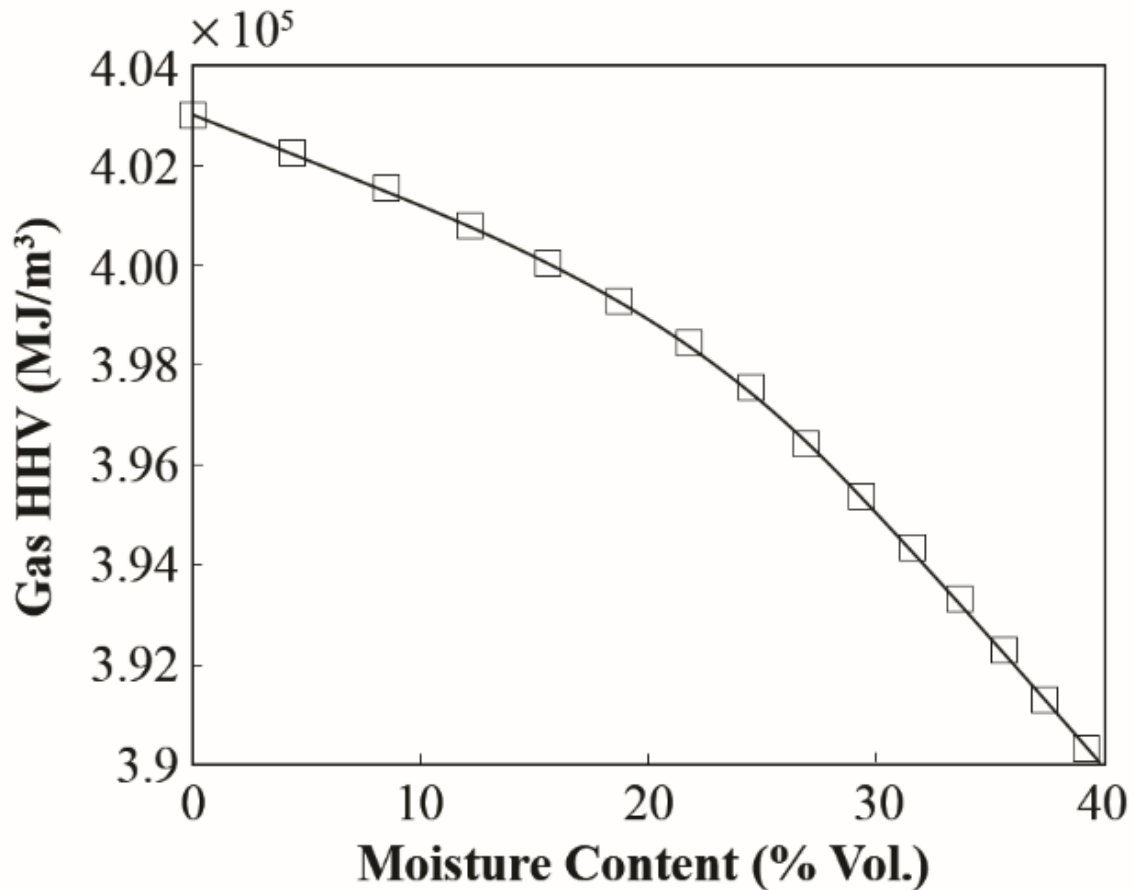


Figure 8. Calorific value changes of produced gas versus moisture content

In Figure 8. the gas High Heating Value behavior versus moisture content amount is presented. It can be observed that the gas calorific value decreases considerably as moisture content increases. It is displayed that, by raising the moisture content from 10% to 30% the gas calorific value

declines from 4.01×10^5 to 3.95×10^5 MJm^{-3} ; this reduction is mainly due to vapor content increase in the gas composition. Since the cold gas efficiency is considered a crucial factor in biomass gasification, the impact of moisture content on the cold gas efficiency is studied as depicted in Figure 9.

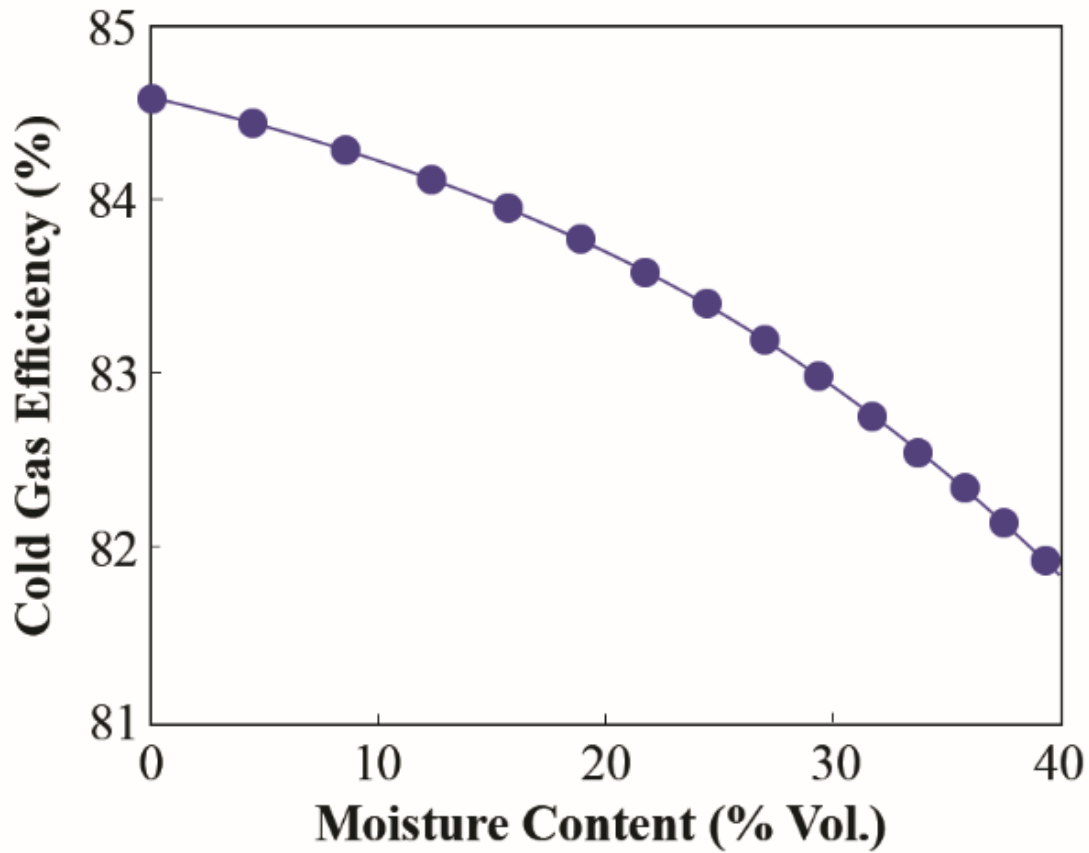


Figure 9: The cold gas efficiency variation versus moisture content

The result reveals that as moisture content is increased, the cold gas efficiency is decreased. It is observed that for moisture content of 10%, the corresponding cold gas efficiency is approximately 84.5% while by increasing the moisture content up to 30% the cold gas efficiency declines to 82.7%.

Figure 10., displays the effect of SOFC temperature variation on power and efficiency of the system. As illustrated, the higher temperature of the SOFC leads to more output power of the system, whilst by increasing temperature from 1200 K to 1400 K the corresponding power of the system is considerably enhanced from 305 kW to 360 kW.

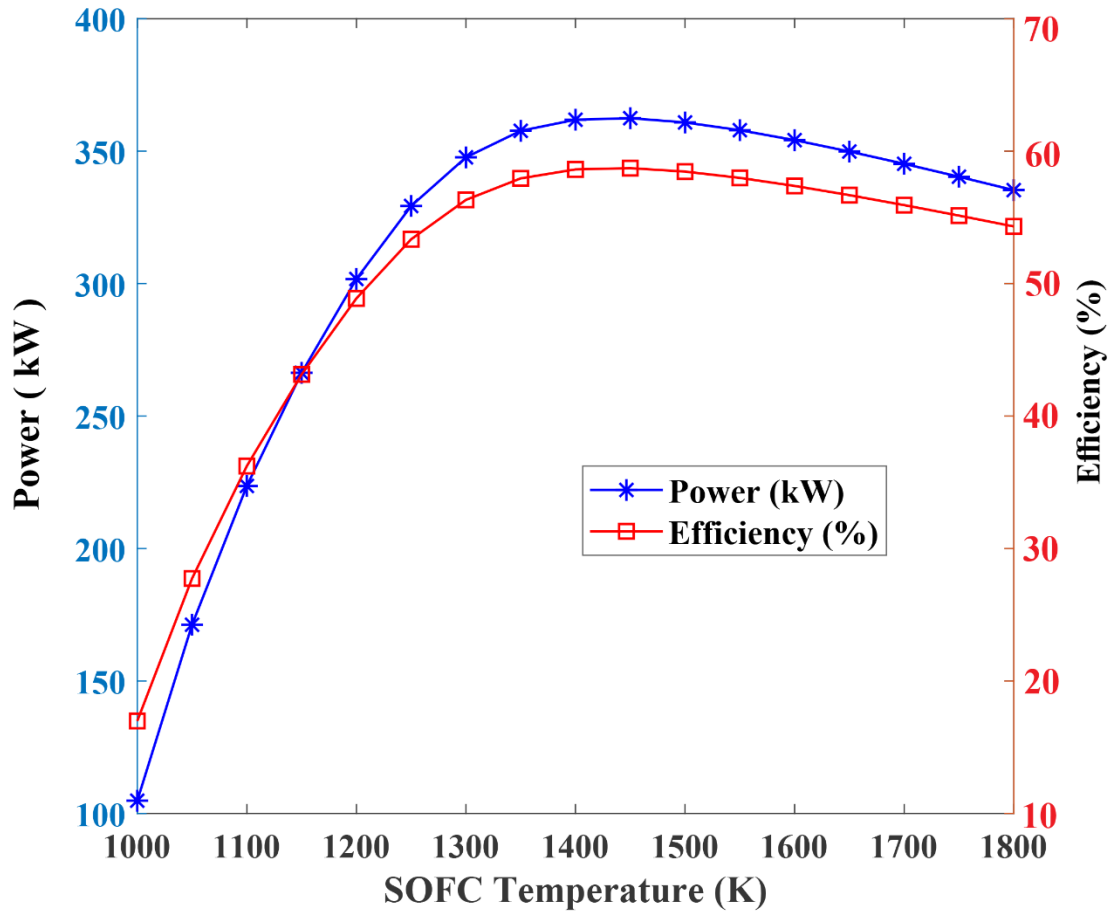


Figure 10: Power and Efficiency versus SOFC temperature variation

A similar trend is depicted for the efficiency of the system, where the efficiency will be improved about 7% when the operation temperature is boosted from 1200 K to 1400 K. Figure11., demonstrates the SOFC temperature variation effect on the efficiency and heat generation of the integrated system. The results prove that, since a lower operating temperature leads to more

polarization losses in SOFC system, consequently, heat generation of the system will be increased significantly.

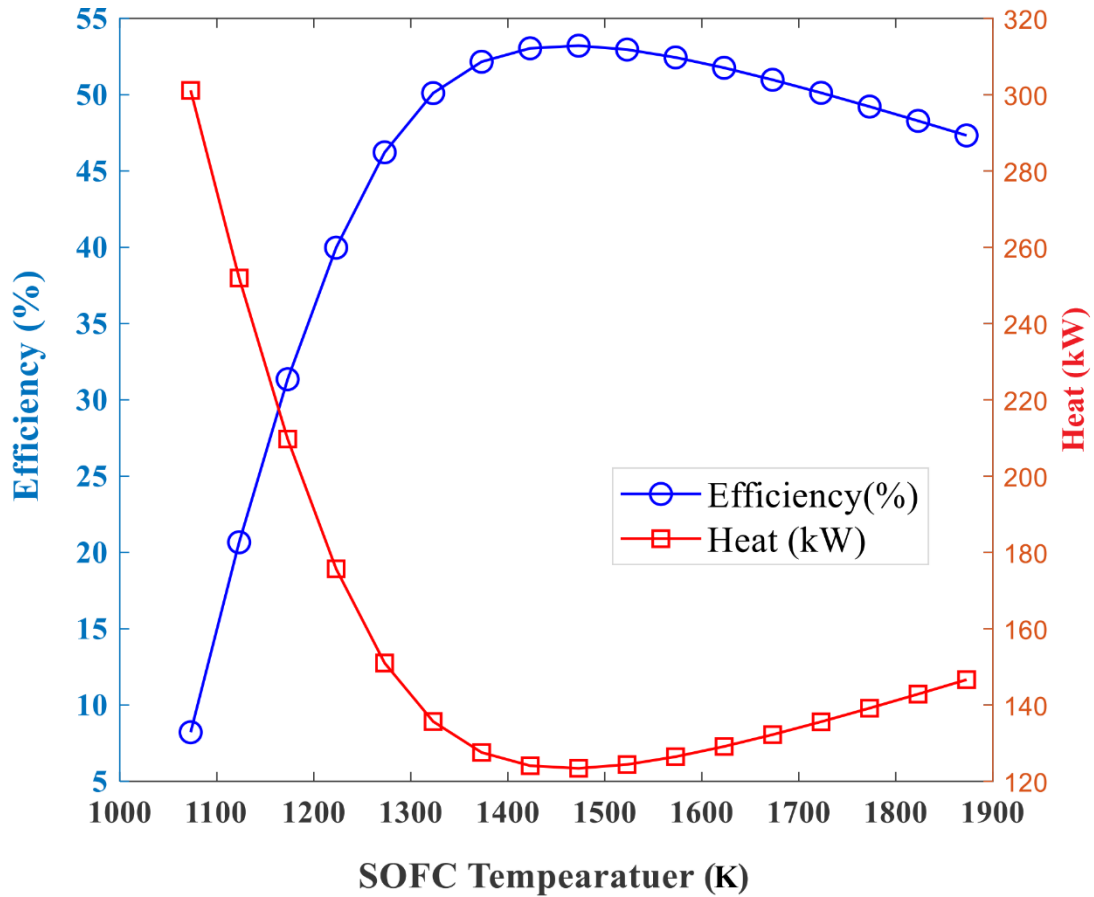


Figure 11: Efficiency and heat generation versus SOFC temperature variation

The heat generated by the system declines while the temperature raises to approximately 1470 K, where it starts a slight enhancement. In essence, the entropy-generated heat will be greater than the polarization-induced heat that will lead to a slight increment in the generated heat. As it is indicated the maximum efficiency of the system is gained at corresponding SOFC working temperature of about 1450 K. It can be seen that by raising SOFC temperature from 1200 K to 1400 K, the efficiency improves about 19% while at similar SOFC temperature, the heat generation

of the system decreases significantly. This implies that SOFC temperature has contradictory effects on system efficiency and heat generation.

From above analysis it can be concluded that two vital parameters on the performance of an integrated gasifier SOFC/GT system are biomass moisture content and working temperature. In the proceeding section, the effect of employing a solar dryer on the power and efficiency of the system will be discussed employing two different scenarios. Based on the results and tables obtained from air flow and time interval of product drain, it is concluded that these two factors have a significant effect on the reduction of moisture content leaving the solar dryer.

It should be noted that the input biomass moisture content is assumed to be about 27-30 (Vol.%) when entering the dryer. Other influential factors such as the Environment Initial Relative (EIR), and the inlet air temperature to the dryer are almost identical. Therefore, the initial velocity of air flow (air flow mass) is the only highly influential operation parameter on the drying rate.

At the first scenario two factors are considered; first, the air mass flux to the solar dryer is considered to take three values of 0.011, 0.0066, and 0.0048 $\text{kgm}^{-2}\text{s}^{-1}$, whereas the second factor, that is the drying and discharging time of biomass, is assumed to be 15 minutes. Briefly in the Table 9, the result of combination of three air mass flux and the drain time of 15 minutes is illustrated on the resultant output moisture content of biomass from solar dryer. At the first scenario $t_1 = 15 \text{ min}$ while $Q_1=0.011 \text{ kgm}^{-2}\text{s}^{-1}$, $Q_2=0.0066 \text{ kgm}^{-2}\text{s}^{-1}$, $Q_3=0.0048 \text{ kgm}^{-2}\text{s}^{-1}$.

Table 9. The combination of drain time and air mass flow and corresponding moisture content

Alternatives	Moisture Content (%)
Q_1t_1	14.2
Q_2t_1	17
Q_3t_1	20

According to Table 9. it can be found that the higher the air flow mass, the faster the input biomass dries. The main reason behind it is, by increasing the flow of drying air, pressure difference of water between biomass and drying air will be increased. As a result, the moisture transmission rate of biomass to drying air will be increased consequently the biomass will be dried in faster rate. Figure 12., depicts the variations of the first scenario impact on the entire system's efficiency.

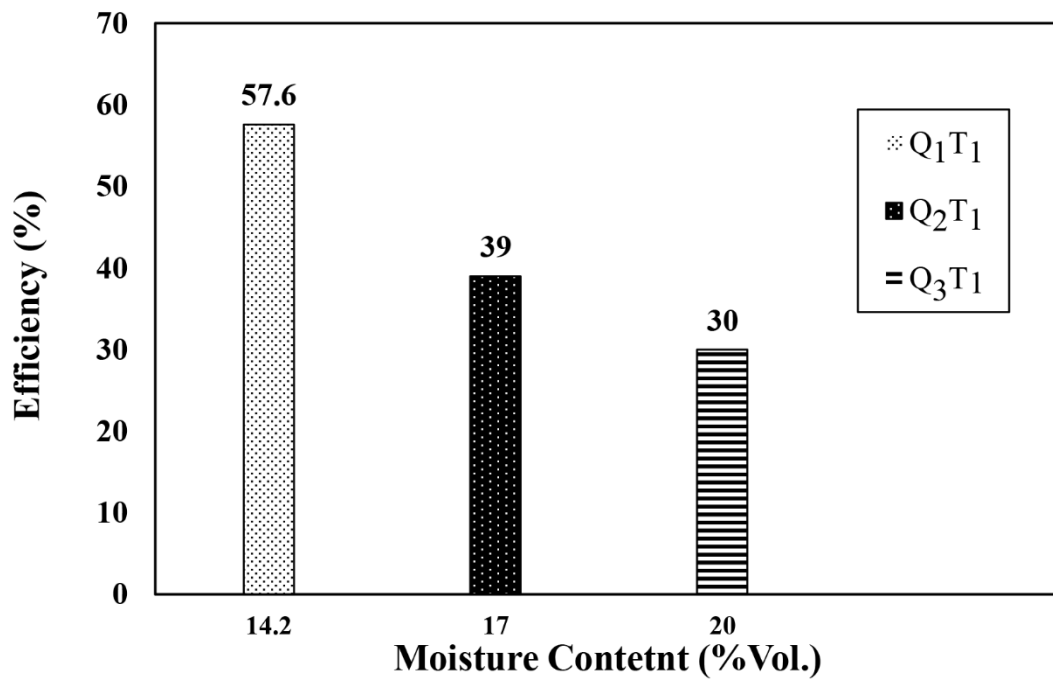


Figure 12. The effect of output moisture content of dryer regards to first scenario on the efficiency

From Figure 12., it can be seen that the rate of moisture loss for biomass at the first steps of the drying process is faster, individually at higher mass flow rates of $Q_1=0.011 \text{ kgm}^{-2}\text{s}^{-1}$ and consequently the system efficiency is proved higher performance regarding the lower moisture content of biomass. The second scenario employs the same three air flow mass to the solar dryer as of the first scenario, i.e. 0.011, 0.0066, 0.0048 $\text{kgm}^{-2}\text{s}^{-1}$ while using a longer drain time of biomass, i.e. 30 minutes. In the Table 10, the effect of combination of three air mass flux and the

drain time of 30 minutes is presented on the resultant output moisture content of biomass from solar dryer.

Table 10. The combination of drain time of 30 min and air mass flow and corresponding moisture content

Alternatives	Moisture Content (%)
Q_1t_2	13
Q_2t_2	16
Q_3t_2	20

Figure 13., represents the entire system's efficiency in response to three flow rates and drain time of 30 minutes employed for the second scenario. By comparing these results, it can be observed that however by increasing drain time from 15 to 30 minutes at the same air mass flow rate of $Q_1=0.011 \text{ kgm}^{-2}\text{s}^{-1}$ the moisture content of output biomass is decreased down to 13 %, the overall efficiency of the system is diminished from 57.6% to 51%. The results demonstrated in this section are gone beyond previous findings and approved that the moisture content of lower than about 15% is not desirable for the system.

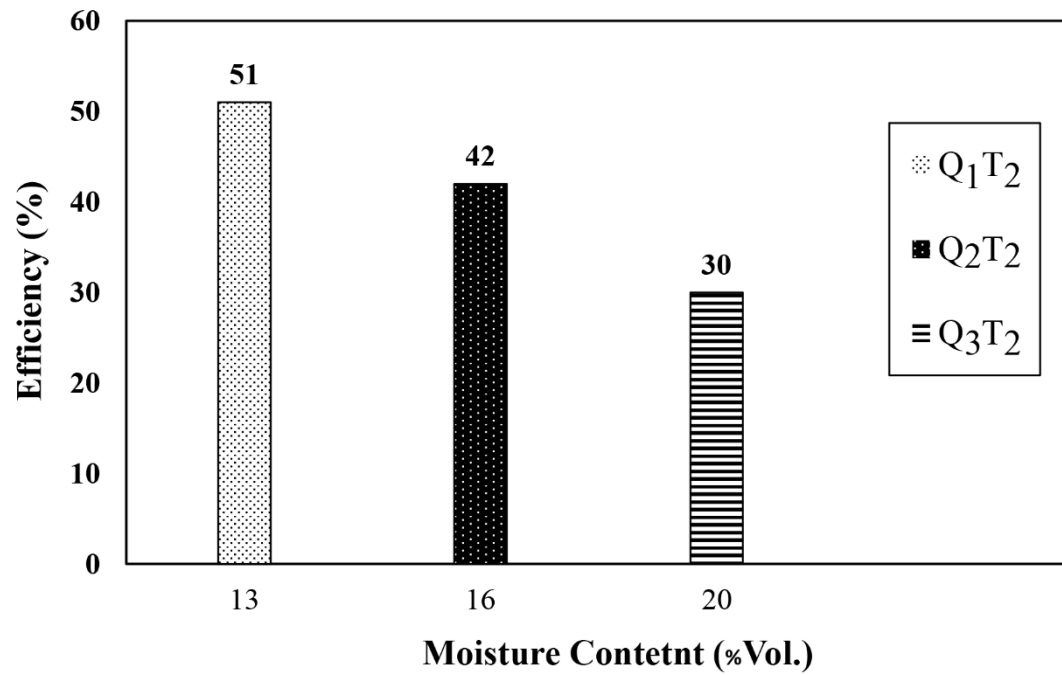


Figure 13. The effect of output moisture content of dryer regards to second scenario on the efficiency

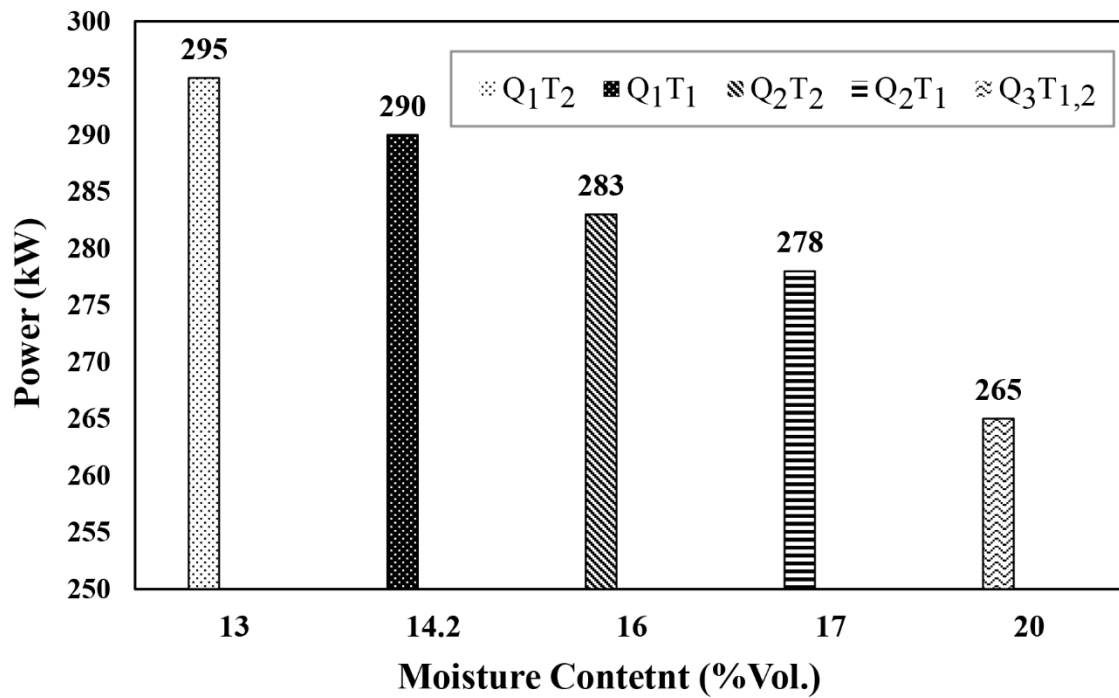


Figure 14. The effect of moisture content of dryer regards to two scenarios on the power

In Figure 14., the effect of output moisture content of both scenarios on the output power of system is investigated. The results suggest that by decreasing moisture content, the output power of the system will be increased. For instance, by declining moisture content from 20% to 14.2% output power generation of the system improves from 265 kW to 290 kW. Moreover, the maximum power of the whole system under studied conditions is 295 kW when the mass flow rate is $0.0011 \text{ kg/m}^{-2}\text{s}^{-1}$ and the drain time is 30 minutes. Interestingly, the maximum efficiency of the system is achieved at mass flow rate of $0.0011 \text{ kg/m}^{-2}\text{s}^{-1}$ and the drain time of 15 minutes. The results indicate that by decreasing approximately 6% in moisture content of biomass, the overall power generation of the proposed system will be enhanced about 8.5 % which is a desirable result for decision makers.

5. Conclusion

In this study, a performance analysis of an integrated solar dryer with a Gasifier-SOFC-GT system has been studied. Since biomass moisture content plays a key factor on the hybrid system performance, the effect of alternating moisture content on the key parameters such as the gasifier temperature, the SOFC temperature, fuel calorific value as well as the efficiency and power output of the overall hybrid system have been examined and discussed. In summary some key findings of this paper can be concluded as: (1) The higher reaction temperature results in more H_2 and CO concentration in generated syngas hence, the cold gas efficiency and the HHV are enhanced significantly. (2) Employing solar dryer to reduce moisture content of biomass leads to an improvement of efficiency up to 27.6%. (3) Reducing the moisture of biomass, improves the power output and efficiency of the hybrid system from 265kW and 30% up to 295 kW and 57.6%, respectively. (4) The best efficiency performance of system under investigated conditions is achieved by the 15 minutes drain time and the air mass flow rate of $0.011 \text{ kgm}^{-2}\text{s}^{-1}$, while the

best power generation of the system is obtained employing the 30 minutes drain time and the air mass flow rate of $0.011 \text{ kgm}^{-2}\text{s}^{-1}$. (5) It can be concluded that a solar dryer as a sustainable approach proposes a practical and environmentally friendly technic to enhance such a hybrid systems performance. For future works, it is suggested to conduct the exergy-economic evaluations of the designed system considering different biomass feedings into the system.

6. Acknowledgement

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7. Nomenclature

Solar Dryer

C	Coefficient of discharge (m)
A_a	Collector surface area
C_p	Specific heat of air (J/kgK)
h	Enthalpy (kJ/kg)
h_1	Enthalpy of hot air in dryer chamber (kJ/kg)
h_2	Enthalpy of dryer outlet air chamber (kJ/kg)
G_T	Incident solar radiation (W/m^2)
M	Air mass flow rate (kg/s)
$\dot{m}$	Air mass flow rate ($\text{kg}/\text{s m}^2$)
P	Atmospheric pressure (bar)
P_{vs}	Partial vapor pressure (bar)
q_c	Useful collected heat (W/m^2)
q_{loss}	Total heat losses (W/m^2)
q_{drying}	Heat consumed for drying process (W)
q_{heater}	Heat provided by heating channel (W)
q_{fan}	Heat consumed by fan (W)
η_c	Efficiency (%)
ϕ	Relative humidity, decimal
w	Humidity ratio, decimal

Down-Draft Gasifier

n_{H_2}	Hydrogen moles (kmol)
n_{CO}	Carbon monoxide moles (kmol)
n_{CO_2}	Carbon dioxide moles (kmol)
n_{H_2O}	Water moles (kmol)
n_{CH_4}	Methane moles (kmol)
n_{N_2}	Nitrogen moles (kmol)
n_{O_2}	Oxygen moles (kmol)
n_c	Carbon moles (kmol)
C	Carbon content in biomass (w%)
H	Hydrogen content in biomass (w%)
O	Oxygen content in biomass (w%)
K	Equilibrium constant

ΔG	Change in Gibbs function
h	Enthalpy ($\text{kJ kmol}^{-1}\text{K}^{-1}$)
LHV	Lower heating value (kJ kg^{-1})
n	of oxygen per kmol of biomasskmol
w	of water per kmol of biomasskmol
m	of steam per kmol of biomasskmol
T	Temperature (K)
P	Pressure (bar)
MC	Mass of water per mass of wet biomass
$\bar{h}_i$	Specific enthalpy of species i
T_g°	Temperature of species i
$G_{y_{fuel}}$	Gas yield ($\text{Nm}^3\text{kg}^{-1}\text{fuel}$)
HHV _{PG}	HHV of product gas (MJNm^{-3})
Heat _{aer}	Endothermic reaction heat (MJkg^{-1})
CGE	Cold Gas Efficiency

Solid Oxide Fuel Cell

A	Area (m^2)
A_{opt}	Area of active TPB (m^2)
D	Mass diffusivity ($\text{m}^2 \text{s}^{-1}$)
D_w	Width of a corrugation (m)
D_p	Average diameter of pores
E	Activation energy (kJ kmol^{-1})
F	Faraday's constant (kmol^{-1})
L	Length (m)
L_{opt}	Activation energy (Jmol^{-1})
i	Current density (Am^{-2})
i_o	Exchange current density (Am^{-2})
j_L	Limiting current density (Am^{-2})
M	Molecular weight (kgkmol^{-1})
n	Molar flow rates (kmol^{-1})
ne	Number of electrons
P_{TPB}	Partial pressure (bar)
P	Operating pressure (bar)
Q_{cell}	Heat generation rate (W)
r	Ohmic resistance (Ω)

R	Universal gas constant ($8.134\text{Jmol}^{-1}\text{K}^{-1}$)
k	Fuel cell components
T	Cell temperature (K)
U_f	Fuel utilization factor
V_{ocv}	Open circuit voltage (V)
V_{nerst}	Nernst potential (V)
η_{act}	Activation polarization (V)
η_{conc}	Concentration polarization (V)
V_{loss}	Voltage losses (V)
η_{ohm}	Ohmic polarization (V)
$\dot{W}_{el}$	Electrical power (W)
z	Reacted hydrogen molar follow rate ($kmols^{-1}$)
α	Charge transfer coefficient
β	Ohmic resistance (Ω)
δ	Pre exponential factor ($\Omega^{-1}\text{m}^{-2}$)
ϕ	Porosity
γ	Pre-exponential coefficient
η	Over potential (V)
λ_{air}	Stoichiometric ratio
σ	Electrical conductivity ($\Omega^{-1}\text{m}^{-1}$)
ψ	Tortuosity

Gas Turbine

$\dot{W}_T$	Turbine power
$\dot{W}_C$	Consumed power from the air compressor
$\dot{W}_{GT}$	Gas turbine net electrical power
μ_g	Generator efficiency
μ_m	Mechanical efficiency
TTT	Turbine inlet temperature

Subscript and Superscript

an	Anode
ca	Cathode
e	Exit
i	Inlet
f	fuel
OCV	Open circuit voltage
TPB	Three-Phase boundary

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