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# NUMERICAL MODELING OF FOOD WASTE PELLET GASIFICATION THROUGH A DOWNDRAFT GASIFIER

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***Abstract***

***Numerical modeling of a food waste pellet downdraft gasifier was carried out in this research. The model was created in Solid works and exported to ANSYS FLUENT in order to simulate non-premixed combustion of biomass fuel. The proximate and ultimate analysis of the pellet as well as the heating value were carried out based on ASTM Standards to determine the required properties of the food waste pellet for the simulation. The model inherent to ANSYS FLUENT contains the same atomic species (C, H, N, O, and S) as the biomass tested. Result showed that the mass fractions of CO, $H_2$, $N_2$, $CO_2$, $CH_4$, $H_2O$ and$C_2H_4$at the exit of the gasifier are 35.81%, 7.89%, 44.49%, 6.89%, 2.15%, 2.11%, 0.65% and 0.0076% respectively using the food waste pellet as fuel.***

***Keywords:*** *Biomass, Downdraft gasifier, Discrete phase model, Equilibrium model, Turbulence*

**1.0Introduction**

Fossil fuels are the biggest sources of energy used by the world. Fossil fuels are limited and the emitted gases by the burning of fossil fuels have very dangerous effect on our environment. Presently the power generated in Nigeria by the use of fossil fuel is not enough to meet the energy needs of the country. On a rough evaluation, only about 54.4% of Nigerians are connected to the national energy grid, according to the World Bank data as at 2017 [1]. This percentage of Nigerians who actually have electric power supplied to them still suffer electric power problems, about 60% of the time [2]. It is very important to harness the renewable energy sources or clean energy sources such as the solar, wind, biomass which have no negative impact on our environment.

Food waste constitute a great percentage of municipal solid wastes generated across Nigeria [3,4]. A study by Ahmed and Gupta [5] have shown that food waste is a potential source of power generation and energy conservation, ultimately reducing the amount of residual waste through recycling using bio-energy systems such as bio-methanation, gasification, pyrolysis and incineration. Bio-energy systems constitute biomass resources, supply systems, technologies for conversion from biomass to energy and energy services [6]. By wasting food we are wasting energy. Food waste has critical effect on our environment, rotting food releases methane gas, which the US agency (EPA) say is 20 times more damaging to environment than carbon dioxide.

Biomass gasification is a complicated chemical process during which fuel goes through pyrolysis, oxidation and reduction stages [7]. Syngas production is the result of the gasification process. Biomass gasification produces lower amounts of emissions compared to combustion. Almost all types of biomass including wood fuel with high moisture agriculture residues and even municipal waste can beused for the gasification process [8]. Several researchers have presented modeling of the gasification process using equilibrium model such as [9] for coal gasification simulation, [10] and [11]. Yueshi et al. [12] developed a two-dimensional computational fluid dynamics (CFD) model to study the gasification process in a downdraft configuration considering drying, pyrolysis, combustion and the gasification reactions. Rukshan and Souman [13]; Janajreh and Shrah [14] also presented modeling and experimental gasification using different wood as fuel. Colomba [15] formulated a one-dimensional unsteady model for biomass gasification in a stratified concurrent (downdraft) reactor. Heat and mass transfer across the bed were coupled with moisture evaporation, biomass pyrolysis, char combustion and gasification, gas-phase combustion and thermal cracking of tars. Numerical simulation was used to predict the influence of model parameters, kinetic constants and operational variables on process dynamics, structure of the reaction front and quality of the producer gas. This study examines the numerical gasification of food waste pellet in a downdraft gasifier in-order to predict the mass fraction of syngas at the exit of the gasifier.

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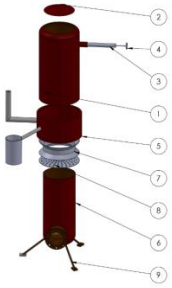
**2.0Methodology**

**2.1 Description of Gasifier Model**

The schematic diagram of the downdraft gasifier installed at Josh Engineering Services workshop, opposite Uselu market, Benin City is shown in the figure 1. This gasifier is considered for this study.



1. Hopper
2. Cover
3. Air inlet pipe
4. Air inlet regulator
5. Outlet casing of reaction zone
6. Ash pond
7. Reaction zone
8. Grate
9. Stand

Figure 1. The Modelled Downdraft gasifier

**2.2 The Model setup**

In this analysis, a computational fluid dynamics model of the gasifier was developed using commercial CFD software ANSYS FLUENT version19. The geometry was designed using Solidworks and then imported into ANSYS Fluent design modeler. The geometry andthe structured mesh are shown in Figure 2 and Figure 3 respectively. The number of nodes was 326,067 and the number of elements was 72356,orthogonal quality was 0.790535 and aspect ratio was 2.87 of the generated mesh model. A finite volume structured mesh approach was introduced to solve the Reynolds-average Navier-Stokes (RANS) equations. Turbulence flow field of the gasifier was modeled using standard k epsilon. During the modeling, discrete phase model (DPM)was applied by considering the Eulerian-Lagrangian approach.

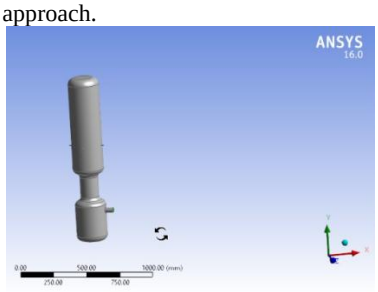



Figure 2: The Gasifier Geometry

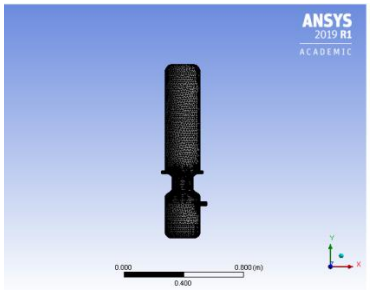



Figure 3: The Mesh

**Modelling Assumptions**

The assumptions for this model are stated below

a) The flow is steady and three-dimensional.
b) The flow inside the domain is considered as incompressible and turbulent.
c) Cylindrical particles are used to define the fuel particles.
d) The chemical reactions are faster than the time scale of the turbulence eddies.
e) The no-slip condition is imposed on inside wall surfaces.
f) Evenly distributed particle regime is utilized.
g) Discrete phase model was used, given the small particle size compared to the reactor volume.

The equation for mass flow, momentum and energy are given by equations (1) to (3) respectively [16].

$$\nabla . \rho \vec{v} = St_{ce} \quad (1)$$

$$\nabla . (\rho \vec{v} \vec{v}) = -\nabla \mathrm{p} + \lambda \nabla . \left[ \left( \nabla \vec{v} + \nabla \overrightarrow{v^T} \right) - \frac{2}{3} \nabla . \vec{v} \right] + \rho \vec{g} + St_{me} \quad (2)$$

$$\nabla . (\rho \vec{v} H) = \nabla . \left( \frac{Kt}{Cp} \nabla H \right) + St_{ee} \quad (3)$$

The energy equation is used for non-adiabatic, non-premixed combustion problem as the viscous dissipation appears in the energy source term ($St_{ee}$). The conduction and species terms from the energy equation are combined in the first term on the right hand side of the equation in this model where the total enthalpy is defined as the sum of the mass fraction and enthalpy for the i$^{th}$ species given by equation (4)

$$H = \sum_i Y_i \int_{T_{ref.i}}^{T} C_{p.i} dT + h_i^o (T_{ref.i}) \quad (4)$$

Where $h_i^o (T_{ref.i})$ is the enthalpy of formation of species *i*at the i$^{th}$reference temperature, $Y_i$ is the mass fraction of specie i. This term negates the need for the heat of reaction source term since the heat of formation is included. The energy equation also include a radiation source term defined by equation (5).

$$-\nabla . qr = aG - 4an^2 \varphi T e^4 \quad (5)$$

**Turbulence Model**

Standard k- epsilon turbulence model was considered for simulation of flow. The k and ϵ was derived from the transport equations (6) and (7) [16].

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k \vec{v}) = \frac{\partial}{\partial x_j}\left[\left(\frac{\lambda}{\xi_k}\right)\frac{\partial k}{\partial x_i}\right] + 2\lambda_k E_{ij}.E_{ij} - \rho\varepsilon \quad (6)$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_i}(\rho \epsilon \vec{v}) = \frac{\partial}{\partial x_j}\left[\left(\frac{\lambda}{\xi_\epsilon}\right)\frac{\partial \epsilon}{\partial x_i}\right] + C_{1\epsilon}\frac{\epsilon}{k}2\lambda_k E_{ij}.E_{ij} - C_{2\epsilon}\rho\frac{\epsilon^2}{k} \quad (7)$$

The eddy viscosity, λ, is computed by combining k and $\epsilon$ as in equation (8)

$$\lambda = \rho C_\mu \frac{\epsilon^2}{k} \quad (8)$$

Where $C_{1\varepsilon}$, $C_{2\varepsilon}$, and $C\mu$ are all constants given as 1.44, 1.92 and 0.09 respectively. The turbulent Prandlt numbers for k and ε, $\xi_k$ and $\zeta_\varepsilon$, are given as 1.0 and 1.3, respectively. For this model, no user-defined source terms were used.

**Species Transport Model**

The specie model was deployed to model biomass gasification. The species transport model has been chosen to model the chemical reactions inside the gasifier and to find out the composition of various species like Carbon II oxide (CO), Carbon IV oxide ($CO_2$), Nitrogen ($N_2$), Hydrogen ($H_2$), Ethylene ($C_2H_4$) and Methane ($CH_4$). The common form of the transport equations for each specie is given in equation (9). [16]

$$\frac{\partial}{\partial t}(\rho m m_i) + \nabla.(\rho \vec{v} m m_i) = -\nabla(\rho D m_i \nabla m m_i) + R_i \quad (9)$$

**Chemical Reaction Model**

Chemical reactions in biomass gasification model involve the following processes: drying, devolatilization of biomass, homogenous reaction and heterogeneous reactions [16].

**a. Drying**

The drying model is given by equation (10)

Moist feedstock+ Heat → Dry feedstock+ $H_2O$ (10)

**b. Devolatilization**

The devolatilization model for biomass is given by equation (11).

$$Dry\ Biomass \rightarrow Char + Ash + Moisture + Volatiles \quad (11)$$

The reaction kinetic rate is expressed in single-step Arrhenius fashion by equation (12)

$$k = Apexp\left(-\frac{Ea}{RTe}\right) \quad (12)$$

The pre-exponential factor and activation energy are given in Table 1

**a. Volatile Reduction**

A qualitative and quantitative knowledge of the devolatilization species is essential for realistic modelling of the coupled thermochemical conversion of food waste pellet into syngas [14]. Therefore, the volatiles, which are represented by a single molecule of the form $CH_aO_bN_dS_e$ are decomposed according to equation (13) which holds a strict balance of mass and heat into gas components ($CO_2$, $H_2O$, $N_2$).

$$CH_aO_bN_dS_e + v(O_2 + 3.76N_2) \rightarrow wCO_2 + xH_20 + yN_2 + zH_2S \quad (13)$$

The empirical formula of biomass and volatiles are based on proximate and ultimate analysis of biomass chemical formula.

**b. Gas Phase Homogeneous Reactions**

The various homogeneous reactions are given by equations (14) to (17) [16; 17; 18].

$$C0 + 0.5O_2 \rightarrow CO_2 \quad (14)$$

$$H_2 + 0.5O_2 \rightarrow H_2O \quad (15)$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (16)$$

$$C_2H_4 + O_2 \rightarrow 2CO + 2H_2 \quad (17)$$

**c. Particle Surface Heterogeneous Reaction:**

Multiple surface reaction models were used to model the food waste particles oxidation and gasification reactions. The heterogeneous equations are given by equations (18) to (21) [16; 19]

**a. Oxidation reaction**

$$C_{(s)} + O_2 \rightarrow CO_2 \quad (18)$$

**b. Boudourd reaction**

$$C_{(s)} + CO_2 \rightarrow 2CO \quad (19)$$

**c. Hydrogasification reaction**

$$C_{(s)} + 2H_2 \rightarrow CH_4 \quad (20)$$

**d. Water-gas reaction**

$$C_{(s)} + H_2O \rightarrow CO + H_2 \quad (21)$$

Chemical kinetics of reactions is summarized in Table 1[20; 21; 22; 23].

**Table 1: Kinetic Constants of the reactions**

| S/no | Equation | Pre-exponential factor ($sec^{-1}$) | Activation energy (kJ/mol) |
|---|---|---|---|
| 1 | (13) | 5.3e10 | 88 |
| 2 | (14) | 10e17 | 166.28 |
| 3 | (15) | 1.08e13 | 1.25e06 |
| 4 | (16) | 5.16e15 | 1.3e08 |
| 5 | (17) | 1.0e12 | 1.73e08 |
| 6 | (18) | 1e-11 | 2.49e07 |
| 7 | (19) | 6.35e-11 | 1.62e08 |
| 8 | (20) | 1.18e-13 | 1.49e08 |
| 9 | (21) | 2e-10 | 3.85e07 |

**The Boundary Condition**

The fuel was introduced at the top of the gasifier with a flow rate of 0.0013889kg/s and temperature of 350K. Air was used as gasifying agent and was introduced through the air inlet pipe at a flow rate of 0.0026683kg/s (using equivalence ratio of 0.3) and temperature 400K. The wall of the gasifier is defined as adiabatic wall with no slip condition. Since it is a combustion and eddy dissipation model, a false time stepping is followed to obtain a converged solution with a relaxation factor of 0.01 [23]. Pressure-outlet boundary was assigned to the gas outlet and the mass fraction of individual species were obtained at the outlet of the gasifier model using the probe tool in ANSYS post processing.

**Model Validation**

The model was validated with models of Kirsanovs and Zandeckis [7]and Jayah et al. [24]. Fuel chemical composition (proximate and ultimate analysis of the fuel) and equivalence ratio were similar with other studies in validation. The comparison result is presented in Table 2. The results obtained using similar condition are in close range with results from others models.

Table 2: Model Validation Results

| | Biomass Moisture | Equivalence Ratio | Syngas Composition (%) | | | | |
|---|---|---|---|---|---|---|---|
| | | | CO | $CO_2$ | $H_2$ | $CH_4$ | $N_2$ |
| Jayah et al. [24], | | | 20.2 | 9.7 | 18.3 | 1.1 | 50.7 |
| Present model | 16% | 0.4 | 21.8 | 9.1 | 17.52 | 2.3 | 49.28 |
| Kirsanovs and Zandeckis [7] | | | 22.4 | 9.03 | 18.1 | 0.31 | 50.2 |
| Present model | 14% | 0.39 | 20.12 | 8.91 | 20.43 | 0.46 | 50.08 |

**Feedstock fuel property**

Some common food waste samples were collected from the University of Benin cafeterias, Benin City, Nigeria. It is a complex that comprise of seventeen food restaurants and is located at the back of student's hostels. Four (4) bagswere distributed to each of the food vendors to collect four different food waste samples used for this study (Rice, Yam peel, Potato peel and Eba). Orange peel was sourced from different orange sellers at Uselu market, a popular market in Benin City which is located along Benin Lagos expressway, Benin City, Nigeria. The percentage mass composition of the food waste samples are rice 29%, yam peel 16%, potato peel 14%, orange peel 22% and eba 19%. The selected food wastes were mixed using a food waste mixer to obtain a uniform mixture. The mixed food waste samples was subjected to pelletization process at an ambient temperature of 25$^o$C. The produced pellets has a diameter of 30mm and average height of 100mm. The briquettes were dried under sun for a period of 16days (6 hours daily) in an open area with an average air temperature of 27$^o$C.

The proximate, ultimate analysis and higher heating value of the food waste pellet (dry bases) are shown in Table 3.

Table 3: Proximate, Ultimate Analysis and Heating Value of the Food Waste Pellet (Dry bases)

| **Proximate Analysis** | | **Ultimate Analysis** | |
|---|---|---|---|
| Moisture Content | 4.12% | C | 48.10% |
| Volatile Matter | 79.90% | N | 1.97% |
| Ash | 2.30% | S | 0.094% |
| Fixed Cabon | 13.68% | H | 7.24% |
| Higher heating value | 17.65MJ/kg | O | 40.30 |

**3.0 Results and Discussions**

The temperature distribution, air mass fraction and syngas composition mass fraction contours are presented in this section.

**3.1 Temperature Distribution**

The temperature distribution from the simulation is shown in Figure 4. The maximum temperature recorded is 1771K (1498$^o$C) and occurs at the gasification zone. The drying zone temperature was observed to be 343K (70$^o$C) at the top and increased progressively to 470K at the end of the drying zone as the biomass move downwards towards the combustion area. The temperature of the gas at exit using the probe tool is 594K (320$^o$C).

**3.2 Air Mass Fraction**

The mass fraction of air in the simulation as shown in Figure 5 depicts a maximum value of 1 at the four air inlet pipes to the model gasifier. At the air inlet pipe, air is the only expected substance and hence a value of 1 is justified. A known mass of air is necessary to combine with the known mass of fuel pellet to achieve the desired equivalence ratio for the simulation.

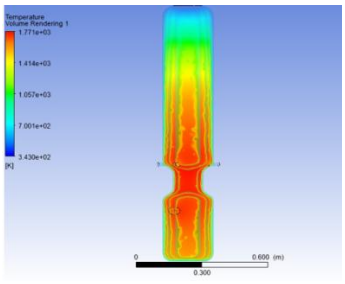


Figure 4: Temperature Contour

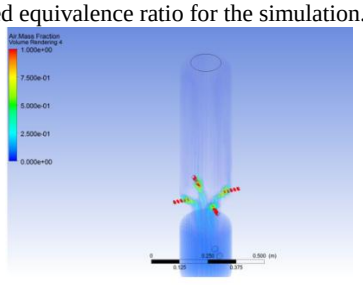


Figure 5: Air Mass Fraction Contour Plot

### 3.3 Syngas Composition

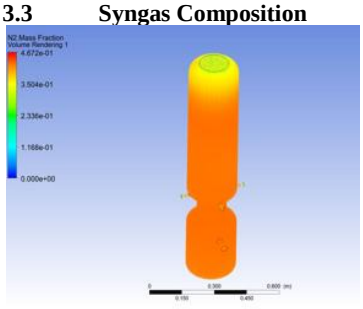


Figure 6: $N_2$ Mass Fraction Contour

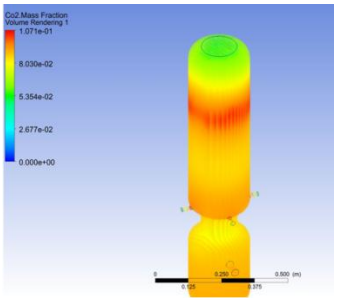


Figure 7: $CO_2$ Mass Fraction Contour

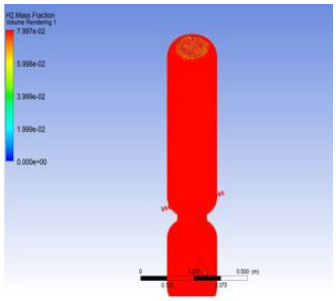


Figure 8: $H_2$ Mass Fraction Contour

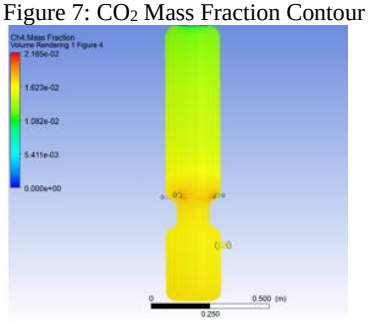


Figure 9: $CH_4$ Mass Fraction Contour

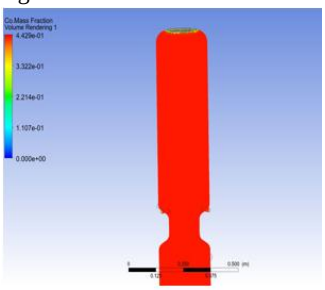


Figure 10: CO Mass Fraction Contour

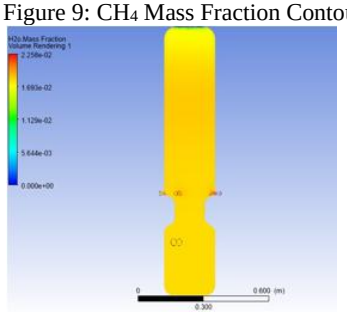


Figure 11 $H_2O$ Mass Fraction Contour

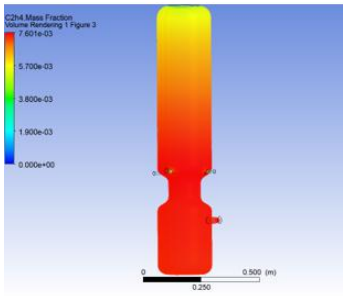


Figure 12: $C_2H_4$ Mass Fraction Contour

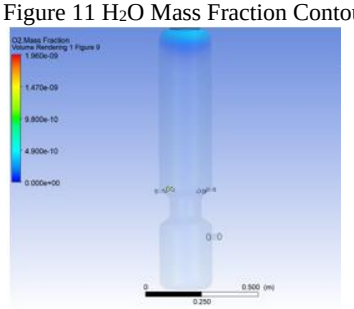


Figure 13: $O_2$ Mass Fraction Contour

Figures 6, 7, 8, 9, 10, 11, 12 and 13 respectively show the contour plots of $N_2$, $CO_2$, $H_2$, $CH_4$, CO, $H_2O$, $C_2H_4$ and $O_2$ mass fractions respectively. Figure 6 shows the highest value of the mass fraction for Nitrogen as 0.4672 which occurs at the gasification zone while the lowest value is 0 and occurs at the top of the gasifier model. The probe value at the exit of the syngas gave a value of 0.4449. Figure 7 shows that the maximum and minimum values of $CO_2$ in the gasifier model are 0.1071 and 0 respectively and occurring at the pyrolysis zone and at the top respectively. The values of $CO_2$ at the exit of the gasifier obtained from the simulation using the probe tool in ANSYS gave a value of 0.0689. Figure 8 depicts the maximum and minimum values of hydrogen in the model gasifier as 0.07997 which occurs at the gasification zone and 0 which occurs at the top of the gasifier. The value of hydrogen gas at the outlet of the gasifier was gotten to be 0.0789. The values for $CH_4$ gas in the simulation result were generally low as can be seen from Figure 9 with the maximum occurring at gasification zone with a value of 0.02165 and a minimum occurring at the top of the gasifier with a value 0. The mass fraction of $CH_4$ at the gasifier exit was gotten from the figure as 0.0215. Also, the maximum values of the mass fractions for CO, $H_2O$, $C_2H_4$ and $O_2$ are 0.4429, 0.02256, 0.007601 and 0.00000000196 respectively while their minimum values are 0 as can be seen from Figures (10), (11), (12) and (13) respectively. The mass fraction contours as expected had their maximum values at the gasification zone while their minimum values occurred at the top or drying zone of the gasifier model. The probe tool in ANSYS CFD post was used to obtain the actual values of each mass fraction at the syngas exit for the various constituents. The result depict high composition of CO and $N_2$ gases in the syngas obtained from food waste pellet, though the CO value is less than the value obtained in [16]. Hagos et al. [25] Dion et al. [26] also presented values of CO between 21% and 44% in wood and rice husk gasification.

## 4. Conclusion

Modeling thermochemical conversion of food waste pellet to produce syngas using a downdraft gasifier was presented in this paper. Air was used as the gasifying agent and the properties of the food waste pellet were obtained from the proximate and ultimate analysis of food waste prepared for this purpose. The model was developed to predict the mass fraction of syngas at exit of the gasifier. Result showed that the mass fractions of CO, $H_2$, $N_2$, $CO_2$, $CH_4$, $H_2O$ and $C_2H_4$ at the exit of the gasifier are 35.81%, 7.89%, 44.49%, 6.89%, 2.15%, 2.11% and 0.65% respectively from the simulation.

## References


[1] World Bank (2020). https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=NG. accessed March 4th, 2020

[2] Aliyu A., Ramli A. and Saleh M., (2013): Nigeria electricity crisis: Power generation capacity expansion and environmental ramifications. Energy, 61(8), pp. 354-367

[3] Adingwupu A. C., Obanor A. I., Aregbe O. and Emifoniye E. U. (2019a). Design and Development of a Food Waste Mixer. The Journal of the Nigerian Institution of Production Engineers. Vol. 23, (2019). 50-60

[4] Adingwupu A. C., Aregbe O. and Erameh A. A. (2019). Performance Evaluation of a Food Waste Mixer. The International Journal of Engineering and Science (IJES). 8(12), 25-29

[5] Ahmed I. I. and Gupta A. K., (2010): Pyrolysis and gasification of food waste: Syngas characteristics and char gasification kinetics. Applied Energy: 87 pp 101–108

[6] McKendry, P (2002). Energy production from biomass (part 1): overview of biomass, Bioresource Technology, 83(1), pages 37-46.

[7] Kirsanovs V. and Zandeckis A. (2015). Investigation of biomass gasification process with torrefaction using equilibrium model. Energy Procedia 72 ( 2015 ) 329 – 336

[8] Lettner F, Timmerer H, Haselbacher P. (2007) Biomass gasification – state of the art description. Gasification Guide. Graz, Austria 2007.

[9] Manfrida G., Bidini G. and Trebbi G. (1990): Modeling coal gasification combined cycle (CGCC). A Future for Energy, Flowers'90.

[10] Ruggiero M. and Manfrida G., (1999): An equilibrium model for biomass gasification processes. Renewable Energy, 16(1-4): 1106-1109

[11] Zainal Z. A., Ali R., Lean C. H. and Seetharamu K. N. (2001): Prediction of performance of a downdraft gasifier using equilibrium modeling for different biomass materials. Energy Conversion and Management, 42(12): pp 1499-1515.

[12] Yueshi Wu, Qinglin Zhang, Weihong Yang and WlodzimierzBlasiak, (2013). A two-dimensional CFD simulation of biomass gasification in a downdraft fixed bed gasifier with highly preheated air and steam. Energy and Fuels 27(6): pp. 3274-3282.

[13] Rukshan J. and Souman R. (2017): Numerical and Experimental Investigation of Equivalence Ratio (ER) and Feedstock Particle Size on Birchwood Gasification. Energies, 10, 1232

[14] Janajreh, I. and M. Al Shrah, (2013): Numerical and experimental investigation of downdraft gasification of wood chips. Energy Conversion and Management, 65: pp. 783-792.

[15] Colomba D. B., (2000): Dynamic behaviour of stratified downdraft gasifiers. Chemical Engineering Science 55, pp 2931-2944

[16] Rahul G., Pankaj J. and Savita V. (2017). CFD Modeling and Simulation of 10kWe Biomass Downdraft Gasifier. International Journal of Current Engineering and Technology. 7(4). pp 1446-1452

[17] Slezak, A., Kuhlman, J. M., Shadle, L. J., Spenik, J. and Shi, S., (2010): CFD simulation of entrained-flow coal gasification: Coal particle density/size fraction effects. Powder Technol. 20(3), pp 98–108

[18] Allesina G., Pedrazzi S., Tartarini P., (2013): Modeling and investigation of the channeling phenomenon in downdraft stratified gasifers. Bioresourses. Technology 146, pp 704–712.

[19] Arnavat P. M., (2011): Performance Modelling and Validation of Biomass Gasifiers for Trigeneration Plants. (Unpublished Doctoral dissertation), University Rovira, Virgili, Spain

[20] Franciso, V., Andres, M., Juan, F. P. and Alfonso, H., (2008): Effect of biomass particle size and air superficial velocity on the gasification process in a downdraft fixed bed gasifier. An experimental and modelling study. Fuel Process. Technology. 89, pp 1076–1089.

[21] Avdhesh, K. S., (2008):.Equilibrium and kinetic modelling of char reduction reactions in a downdraft biomass gasifier: a comparison. Sol. Energy 82, pp 918–928.

[22] Babu, B. V. and Pratik, N. S., (2006): Modelling and simulation of reduction zone of downdraft biomass gasifier: effect of char reactivity factor. Energy Conservation Management. 47, pp 2602–2611.

[23] Murugan P. C. and Sekhar S. J. (2017) Species – Transport CFD model for the gasification of rice husk (Oryza Sativa) using downdraft gasifier. Computers and Electronics in Agriculture 139 Elsevier pp 33–40

[24] Jayah T. H., Aye L., Fuller R. J., Stewart D. F. (2003). Computer simulation of a downdraft wood gasifier for tea drying. Biomass and bioenergy 2003;25: 459–469.

[25] Hagos F. Y., Aziz A. R., Sulaiman S. A. and Mahgoub B. K., (2013): Combustion characteristics of direct injection spark-ignition engine fuelled with producer gas. Energy Educ. Sci. Technol. Part A: Energy Sci. Res., vol. 31, pp. 1683–1698

[26] Dion L, Lefsrud M, Orsat V., Orsat V. and Cimon C. (2013): Biomass Gasification and Syngas Combustion for Greenhouse CO2 Enrichment. BioResources. 8(2). pp 1520-1538.