Computational Modelling of Imbert Type Downdraft Biomass Gasifier using CFX

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Abstract: *Concern over the depletion of fossil fuels in the near future, increasing awareness about environmental pollution and need for energy conservation have proved that biomass is one of the most promising renewable sources of energy. However, efficient processes are required to convert this sources into useful one. So, gasification technology enables the conversion of these sources into a combustible gases, mechanical power and electrical energy. The quantity and quality of biomass differs from place to place. Therefore, designing a gasification technology for a remote areas needs more theoretical and experimental studies. The goal of this article is to develop a comprehensive and predictive kinetic model for the pyrolysis process in a downdraft gasifier, which is predominantly used in many places for biomass gasification. The volatiles and gases released during the pyrolysis process were assumed to crack down further into equivalent amounts of secondary products. In addition to this, a 30kW$_{th}$ downdraft biomass gasifier was modeled and analyzed using the CFX package. Experimental study were carried out on the same gasifier for further validation. The predicted results shows the temperature and mass fraction of combustible products at the outlet of the gasifier for various equivalence ratios.*

Keywords: pyrolysis, CFX, equivalence ratio, feedstock, gasifier, producer gas

1. Introduction

Increasing environmental issues and stepping energy cost of many conventional energy sources lead this biomass gasification as one of promising alternative energy technology. Biomass gasification involves the thermal destruction of biomass in a reducing atmosphere of steam or air (or both) or oxygen to produce a medium or low calorific value gas [1]. The composition of various constituents in the biomass, equivalence ratio and gasification temperature play a major role the quality and quantity of gas produced [2] [3] [4] [5] [6]. Analytical and numerical methods were used to simulate the performance of gasifiers operating at various working conditions. The thermodynamic equilibrium model has been used to predict the composition and calorific value of the producer gas [7] [8] [9]. The final reaction temperature and the producer gas composition in equilibrium are calculated through the energy balance of the process. Rate of pyrolysis reaction is defined based on unit surface area of solid biomass in the kinetic model and the kinetic constants found is applied to any size and shape of the particle [10]. The various kinetic models like one step global models, parallel reaction models with secondary tar cracking and semi-global reaction models. Among the reaction mechanisms, the secondary tar cracking schemes is most widely used schemes which cover most of the possible aspects of pyrolysis reactions [11]. The drying and pyrolysis of a single wood log is investigated and particularly focuses on the associated phenomena, phase change and species transport [12]. Whereas, the combined the pyrolysis and reduction zone models to simulate the global process of biomass gasification and followed a two-step pyrolysis, where the model equations for description of the kinetic rates of the pyrolysis of the biomass were derived using Runge-Kutta method [13]. Artificial intelligence based techniques were also adopted by neural network approach for simulation of the gasification process. A neurological identifier for concentrations of C, H$_2$, CO, H$_2$O, CO$_2$ and CH$_4$ was developed in a residual biomass process [14]. A very few works have been carried out in numerical studies on gasification process using CFD technique. CFD simulations for an entrained flow biomass gasifier was simulated assuming isothermal flow to determine the particle behaviour [15]. CFD model of an entrained flow biomass gasifier wherein, models of finite rate chemistry in the gas phase and char reactions have been added to the standard model. This simulation also stressed on the fact that gasification reactions are not sensitive to the detailed velocity field around particles but more on the residence time [16]. A two-step pyrolysis reaction scheme is used to model the conversion from wood to tar, gas and char [11]. A 2D axisymmetric CFD model of the oxidation zone in a two-stage downdraft gasifier and investigated in detail about the various zone, which is crucial for tar cracking [17]. Numerous experimental studies are done on biomass gasification. The experimental investigation done on downdraft gasifier details that the cold gas efficiency, mole fractions of CO and H$_2$ increase with φ till a value of 0.25 and then decrease [1]. An experiment conducted on a 75kW downdraft gasifier and reported that the increase in gas flow flow rate improves the bed temperature profile and leading to higher conversion of non-combustible components (CO$_2$ and H$_2$O) into combustible components (CO and H$_2$) and thus higher pressure drop [18]. Downdraft gasifier of about 20 kW capacity is experimentally run to compare gasification data for pellets of wood and bagasse [19]. From the literature review done on pyrolysis kinetics and simulation of the same in CFD, it is found that many researchers have analyzed on particle behaviour, combustion of char or on the destruction of tertiary tar. It is seen that not much analysis is done on the temperature distribution along the pyrolysis zone in gasification. Hence, an analysis is done for finding out the temperature distribution along the pyrolysis zone. Also, looking in to the experimental set up size, most of the literatures have a miniature size gasifier. Compared to them, the one located in the campus is considered unique with the larger dimensional differences and capacity. This work deals with the modeling of pyrolysis zone, which is one among the

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four zones in the gasifier. Experimental studies were done on a 30 kW gasifier setup in the campus were used to compare the numerical results. The gasifier is of single throat, imbert type downdraft gasifier. Modeling and simulation of this zone is done using the software ANSYS CFX 13.0.

2. Model Description

To carry out any CFD analysis, definition of various physical phenomena on mathematical terms is very essential. The boundary conditions and other parameters required for establishing the gasification phenomenon have been explained in the forthcoming sections. The schematic diagram of the imbert type biomass gasifier used in this study is shown in Fig.1. The total height of the gasifier is 2040 mm. The diameters of the biomass inlet and gas outlet are 480 mm and 430 mm respectively. The combustion, pyrolysis and drying, and reduction zones have heights of 450 mm, 950 mm and 640 mm respectively. The 435 mm long air nozzle is inclined at an angle of 45°. Since, this study is a 2D analysis, and in order to reduce the complexity, only the outlet portion of the air nozzle is shown inside the gasifier. The air enters through the air nozzle and producer gas leaves through the gas outlet. The feedstock is charged through the biomass inlet.

3. Numerical Modelling

Materials added for analysis are carbon (C), oxygen (O_2), hydrogen (H_2), carbon dioxide (CO_2), water (H_2O), carbon monoxide (CO), methane (CH_4), nitrogen (N_2), wood, char and tar. Materials like O_2, H_2, CO_2, CO, H_2O, CH_4, N_2 were already been defined in the library of materials. Rest of the materials C, char, tar and wood were fed to CFX-preprocessor by customizing it. Same as creation of
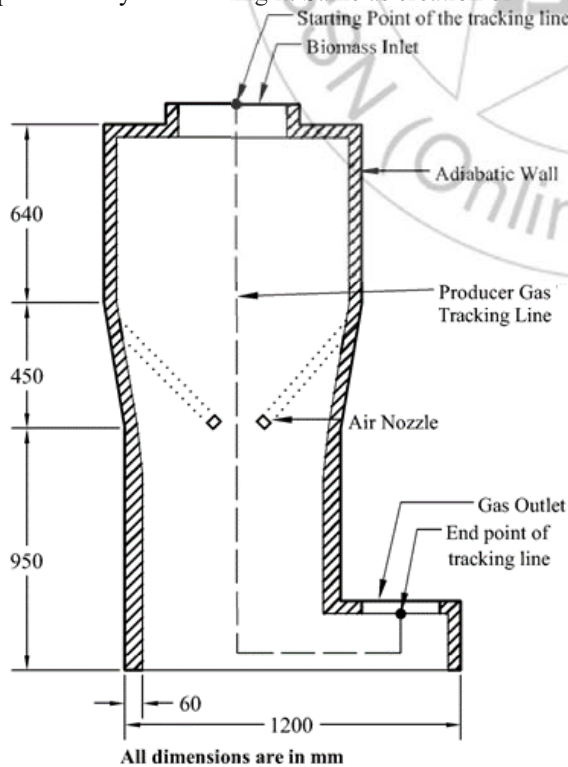
materials, reactions were also created using CFX Command Language (CCL). Each zone was given a set of reactions, along with their reaction rates. The specified reactions and their reaction rates are given in Table 1. The reaction rates considered for reactions 8-11 [9]. Rate of a reaction is determined using the Arrhenius equation, where a large number of rate constants are found to some level of approximation. The Arrhenius equation is given by;

$$K(T) = Ae^{\left(-E_i/RT\right)} \qquad (1)$$

The Arrhenius equation predicts that for positive activation energy, the rate constant increases with temperature. The rates of conversion due to pyrolysis process based on the model explained are considered as given below in Table 1 [11].

3.1 Boundary Conditions

Boundary conditions used in this simulation are inlets, outlets, wall, symmetry planes and openings. The gas outlet is assigned with a pressure outlet boundary and the wall of the gasifier is defined as wall boundary with no-slip condition. According to literatures, the optimum value for equivalence ratio is taken as 0.205 [2] Keeping the biomass consumption rate as 50 kg/hr (0.0138 kg/s) and taking the value for stoichiometric ratio as 6.7338 kg of air/kg of wood (5.22 m3 of air/kg of wood) [2], air flow rate was found out for five different equivalence ratio. Table 2 below shows the air flow rates found out for various equivalence ratios. Simulation was done considering all the five equivalence ratios. The feedstock used in this simulation is considered as rubber seed kernel shell. The proximate and ultimate analysis of the feedstock is given in Table 3 [20] [21].

Table: 1 Rates of conversion during gasification process

Reactions	Pre-exponential factor (s^{-1})	Activation energy $(kJ / kmol)$
$C + O_2 \rightarrow CO_2$	0.005974	302.2174
$H_2 + O_2 \rightarrow 2H_2O$	0.008902	2802.44
$Wood \xrightarrow{k_1} Gas$	1.52E7	-139.2
$Wood \xrightarrow{k_2} Tar$	5.85E6	-119.2
$Wood \xrightarrow{k_3} Char$	2.98E3	-73.1
$Tar \xrightarrow{k_4} Gas$	2.6E6	-108
$Tar \xrightarrow{k_5} Char$	1.0E6	-108
$C + CO_2 \rightarrow 2CO$	3.616E1	77.39
$C + H_2O \rightarrow CO + H_2$	1.517E4	121.62
$CH_4 + H_2O \rightarrow CO + 3H_2$	7.301E-2	36.15
$CO_2 + H_2 \rightarrow CO + H_2O$	4.189E-3	19.21

Figure 1: Schematic diagram of downdraft biomass gasifier

Table 2: Mass flow rate of air for different equivalence ratios

Equivalence ratio (Φ)	Biomass consumption rate (kg/s)	Stoichiometric ratio	Air flow rate (kg/s)
0.18	0.0138	6.7338	0.01673
0.2	0.0138	6.7338	0.01859
0.24	0.0138	6.7338	0.02230
0.26	0.0138	6.7338	0.02416
028	0.0138	6.7338	0.02602

Table 3: Proximate and Ultimate analysis of Rubber seed Kernel Shell

Proximate Analysis (% w.b.)			
Volatile Matter	Fixed Carbon	Moisture Content	Ash
89.4	6.1	4.3	0.2
Ultimate Analysis (%)				
C	H	O	N	S
43.2	6.0	0.55	50.25	0.0

3.2 Convergence of the Simulation

Since the simulation consists of combustion and eddy dissipation models, it is very difficult to obtain a converged solution. Therefore, false time stepping is followed for the turbulence – chemistry interaction, with an under relaxation factor of 0.01 for mass fractions. With this arrangement, the calculation is carried out with 100 iterations.

4. Experimental Description
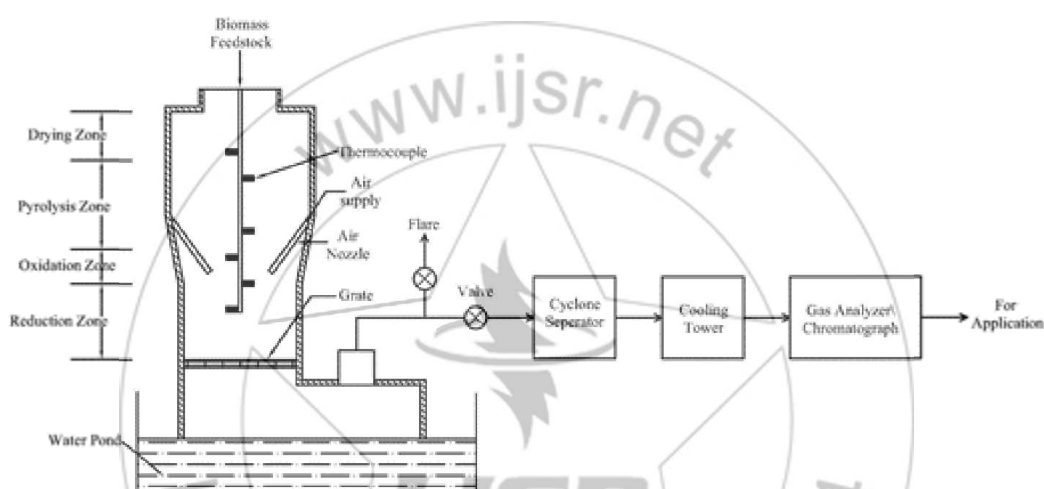
Figure: 2 Experimental setup of downdraft biomass gasifier

The schematic diagram of the experimental setup is shown in Fig. 2. The producer gas leaving from the gasifier contains impurities like tar, unburnt carbon and moisture. The primary cooling and cleaning of producer gas is carried out through the water tray kept below the reactor. The secondary cooling and cleaning system consists of a cyclone separator, cooling tower and a scrubber. The quality and the composition of the producer gas are measured by the gas analyser and gas chromatograph (NUCON-5765). Air nozzle is inclined at an angle of 45° and the flow rate is measured by U-tube manometer. Calibrated K-type (Chromel-Alumel) thermocouples are placed at different locations inside the gasifier and a data logger is used to record the temperature. The bottom region of the gasifier is filled with water to prevent leakage of producer gas. The gasifier is initially filled with charcoal in the reduction zone and the fire is ignited filled with charcoal in the reduction zone and the fire is ignited through the air nozzle [21].

5. Results and Discussions

The pyrolysis process in a gasifier was analyzed for various operating conditions using CFD software ANSYS CFX 13.0 and the variation of important parameters like temperature; producer gas composition and mass flow rate are plotted as contour plots. To prove the suitability of this analysis technique, the experimental results were also analyzed and compared with the analytical ones.

5.1 Mass Fraction of Producer Gas

Among the parameters influencing the performance of a biomass gasifier, producer gas composition plays an important role. Fig. 3 shows the comparative results of the effect of equivalence ratio on the producer gas composition. It is observed that mass fraction of nitrogen decreases with an increase in ϕ up to a value of 0.2 and for higher values of ϕ, mass fraction of nitrogen increases. For higher values of ϕ, with increase in air flow rate, combustion takes place. The fraction of carbon monoxide and hydrogen shows an increasing and decreasing trend just opposite to that of nitrogen. From the graph, it is understood that there is no much variation with the mass fraction of carbon dioxide. The average gas composition of producer gas obtained in the experiment were plotted against the equivalence ratio of the same experimental run. It is seen that the mass fraction of CO and H2 in experimental results reaches highest for
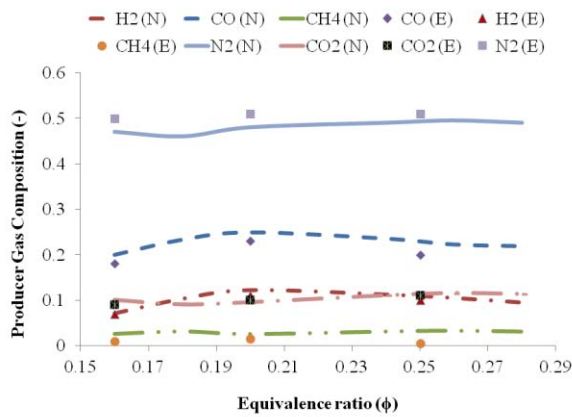
Figure 3: Mass fraction of producer gas against various equivalence ratio

equivalence ratio 0.20 to 25% and 11%, respectively. The mass fractions of CO and H_2 from the numerical study are 26% and 12%, respectively. Comparing mass fractions of nitrogen, from Fig. 3, it can be seen that the experimental results gave a value of 50% for equivalence ratio 0.20 but the numerical study gives 49% for equivalence ratio 0.20. Both the experimental and the numerical results show that mass fraction of nitrogen.

5.2 Calorific Value of the Producer Gas

The variation of calorific value of the producer gas with equivalence ratio is presented in Fig. 4. Calorific value is calculated using the composition of the producer gas. Carbon monoxide and hydrogen are the main components of the producer gas and are responsible for higher calorific value. It is found that at an equivalence ratio of 0.16 the calorific value is the least at 4.3 MJ/Nm³.
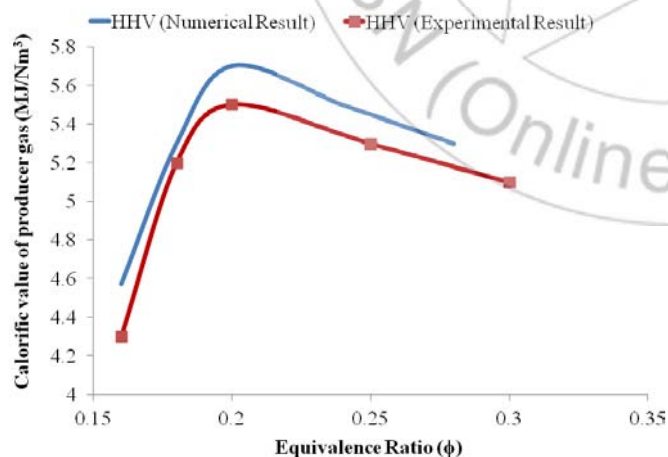
Figure 4: Variation of calorific value of the producer gas with equivalence ratio

By increasing the equivalence ratio at $\phi = 0.20$, the calorific value reaches to a maximum of 5.8 MJ/Nm³ and then follows the decreasing trend. Further increase in equivalence ratio from 0.20, calorific value drops steadily. The optimum equivalence ratio preferred for the better producer gas composition is 0.20.

## 5.3 Temperature Distribution of Producer Gas - Numerical Analysis

Various positions were considered for finding the zone temperature as per the positions considered in the experimental set up. Table 4 shows the variation of temperature at different positions inside the gasifier for different equivalence ratio. It is seen from the table that for all ϕ values, the temperature at the combustion zone varies from 900 K to 1050 K and that of pyrolysis from 650 K to 850 K. It clearly indicates that the temperature profiles pass through a maximum at an equivalence ratio of 0.20. The oxidation zone temperature

Table: 4 Zone temperature variation for different equivalence ratios – numerical result

Equivalence Ratio (ϕ)	Zone Temperatures at various positions (K)					
	T1	T2	T3	T4	T5	T6
0.18	465	686	799	904	971	687
0.20	471	686	801	966	1009	691
0.24	471	695	800	931	965	679
0.26	466	689	798	950	798	651
0.28	476	688	801	966	691	647

depends upon the heat released due to the biomass combustion and air flow rate. As air flow rate increases, it provides more oxygen to oxidize but also brings inert N_2, which acts as a heat carrier and reduces the temperature of the oxidation and pyrolysis zone. The maximum value of temperatures in the pyrolysis and oxidation zones represents the optimum amount of equivalence ratio. Hence, in this case, equivalence ratio 0.20 can be considered the best.

5.4 Temperature Distribution – Comparison of Numerical and Experimental Analysis
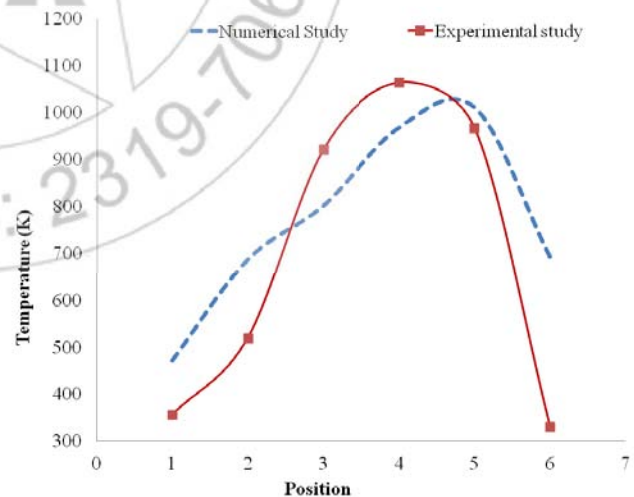
Figure: 5 Temperature distribution of numerical and experimental results

The experiment conducted for 4.5 hours. The air was controlled by the valve to get the expected equivalence ratio, 0.16 to 0.30. The temperatures at various locations in the gasifier measured and plotted for the corresponding equivalence ratio. The Fig. 5 shows the graphical comparison between experimental and numerical studies. The results show that the highest temperature is maintained near the

combustion zone. It is also noted that the pyrolysis zone, where the temperature variations according to the experiment is between 500 and 900 K, This shows that increase in the pyrolysis temperature would lead to the conversion of non-combustible gases like CO_2 and H_2O to combustible gases like CO, H_2 and CH_4. It is also observed that the zone temperatures obtained from the experimental study is on par with the analytical results. The thermocouple sensors placed at the positions, representing the pyrolysis zone temperature shows little difference of 100 K. Hence, it can be said that the pyrolysis model considered for simulation is the appropriate one.

6. Conclusion

The result obtained from numerical simulation for various equivalence ratios 0.16 - 0.28, was analyzed and the same has been compared with the values obtained from the experimental results. Based on this comparative results, the following conclusions are drawn.

- The temperature distribution obtained from both the numerical and experimental studies proves that the approach used in the study, using commercial software CFX, is more appropriate to analyze the pyrolysis of downdraft gasification.
- The study shows that the kinetic modeling approach is a good tool for numerical studies on pyrolysis in downdraft gasification.
- In firing mode (during the experimental run), combustion zone reaches the highest temperature of 1063 K, which is found to be on par with the numerical results. This also proves the effectiveness of this numerical analysis.

The numerical analysis also shows that,
- The mass fraction of CO is maximum when ϕ reaches 0.20.
- The mass fraction of N2 decreases with an increase in ϕ up to 0.20 and for higher values, mass fraction of N2 increases.
- For the equivalence ratio 0.20, 36.63% of the producer gas is combustible.
- The pyrolysis and the combustion zone temperatures are maximum for equivalence ratio 0.20. Therefore, the optimum equivalence ratio of biomass downdraft gasifier is 0.20.

7. Acknowledgement

References

[1] G.Schuster, G. Loffler, G. Weigl and H. Hofbauer,"Biomass steam gasification-an extensive parametric Modeling study", Bioresource Technology, vol. 77, pp. 71-79, 2001.

[2] Pratik N. Sheth and B. V. Babu, "Experimental studies on producer gas generation from wood waste in a downdraft biomass gasifier", Bioresource Technology, vol. 100, pp. 3127-3133, 2009.

[3] Pratik N. Sheth and B. V. Babu, "Production of hydrogen energy through biomass (waste wood) gasification", Hydrogen Energy, vol. 35, pp. 10803-10810, 2010.

[4] L. Fagbemi, L. Khezami and R. Capart,"Pyrolysis products from different biomasses: application to the thermal cracking of tar", Applied Energy, vol. 69, pp. 293-306, 2001.

[5] Asri Gani and Ichiro Naruse, "Effect of cellulose and lignin content on pyrolysis and combustion characteristics for several types of biomass", Renewable energy, vol. 32, pp. 649-661, 2007.

[6] Ruirui Xiao, Xueli Chen, Fuchen Wang and Guangsuo Yu, "Pyrolysis pretreatment of biomass for entrained-flow gasification", Applied Energy, vol. 87, pp. 149-155, 2010.

[7] Z. A. Zainal, R. Ali, C. H. Lean and K. N. Seetharamu, "Prediction of performance of a downdraft gasifier using equilibrium Modeling for different biomass materials", Energy Conversion and Management, vol. 42, pp. 1499-1515, 2001.

[8] S. Jarungthammachote and A. Dutta, "Thermodynamic equilibrium model and second law analysis of a downdraft waste gasifier", Energy vol. 32, pp. 1660-1669, 2007.

[9] Andres Melgar, Juan F.Perez, Hannes Laget and Alfonso Horillo, "Thermochemical equilibrium Modeling of a gasifying process", Energy Conversion and Management, vol. 48, pp. 59-67, 2007.

[10] Pratik N. Sheth and B. V. Babu, "Kinetic Modeling of the pyrolysis of biomass", National conference on environmental conservation (NCEC-2006), BITS-Pilani 2006.

[11] N. Prakash and T. Karunanithi,"Kinetic Modeling in biomass pyrolysis – A review", Journal of Applied Sciences Research, vol.4(12), pp. 1627-1636, 2008.

[12] U. Sand, J. Sandberg, J. Larfeldt and R. Bel Fdhila, "Numerical prediction of the transport and pyrolysis in the interior and surrounding of dry and wet wood log", Applied Energy, vol. 85, pp. 1208-1224, 2008.

[13] Ningbo Gao and Aimin Li.,"Modeling and simulation of combined pyrolysis and reduction zone for a downdraft biomass gasifier", Energy Conversion and Management, vol. 49, pp. 3483-3490, 2008

[14] R. Carasso, E. N. Sanchez and S. Carlos-Hernandez, "Neural network identification for biomass gasification kinetic model", IEEExplore, Proceedings of International Joint Conference on Neural Networks, San Jose, California, USA, pp. 1888 - 1893, 2011.

[15] D. F. Fletcher, B. S. Haynes, F. C. Christo and S. D. Joseph, "Combustion Modeling for an entrained flow biomass gasifier", International conference on CFD in mineral and metal processing and power generation, 1997.

[16] D. F. Fletcher, B. S. Haynes, F. C. Christo and S. D. Joseph, "A CFD based combustion model for an entrained flow biomass gasifier", Applied Mathematical Modeling, vol. 24, pp. 165-182, 2000.

[17] Luc Gerun, Maria Paraschiv, Razran Vijeu, Jerome Bellettra, Mohand Tazerout, Benny Gobel and Ulrik

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Henriksen, "Numerical investigation of the partial oxidation in a two-stage downdraft gasifier", Fuel, vol. 87, pp. 1383-1393, 2008.

[18] Avdhesh Kr.Sharma, "Experimental study on 75kWth downdraft (biomass) gasifier system", Renewable Energy, vol. 34, pp. 1726-1733, 2009.

[19] Catharina Erlich and Torsten H. Fransson, "Downdraft gasification of pellets made of wood, palm-oil residues respective bagasse: experimental study", Applied Energy, vol. 88 (3), pp. 899–908, 2011.

[20] V. Christus Jeya Singh, K. Thyagarajan, P. C. Murugan and S. Joseph Sekhar,"Rubber seed kernel shell as a substitute for wood in a biomass gasifier - An experimental study", Advanced Materials Research, vol. 984-985, pp. 845 - 849, 2014.

[21] Murugan P. C., Joseph Sekhar S., "Numerical simulation of Imbert biomass gasifier to select the feedstock available in remote areas", Environmental Progress and Sustainable Energy, Wiley Online library, DOI:10.1002/ep.12485.

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