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Review on Experimental Investigations and ASPEN Plus Simulations of Fluidized bed Biomass Gasification

[1] Gokul Krishnan S, [2] Pranav Santhosh, [3] Amaljith K Balan, [4] Jibin Mathew, [5] Rupesh S

[1][2][3][4] Mar Baselios College of Engineering and Technology, Thiruvananthapuram, Kerala, India
[5]Assistant Professor, P.E.S College of Engineering, Mandya, Karnataka, India
[1]gokulkrishnans1023@gmail.com, [5] mailtorupeshs@gmail.com

***Abstract*—Gasification is a thermo-chemical process which converts carbonaceous materials into producer gas or chemical feedstock. The present paper deals with a review on experimental investigations and ASPEN Plus simulations of fluidized bed biomass gasification. In experimental investigation the effect of gasifying agent, bed temperature, equivalence ratio (ER), steam to biomass ratio (SBR) and sorbent to biomass ratio (SOBR), bed material are considered. From the review of experimental works, it is observed that the performance of biomass gasification greatly depends on operating parameters such as equivalence ratio, steam to biomass ratio, temperature, gasifying agent, biomass, catalyst and type of sorbent used. On the other hand, review on ASPEN plus simulation deals with the modeling and simulation of biomass gasification through equilibrium model, kinetic model and combination of both. It is found that kinetic models can predict the temporal and spatial variation of gasification products compared to the maximum achievable yield predicted by the equilibrium model. Even though more accurate, kinetic models are more computationally intensive due to the inclusion of reaction kinetics and hydrodynamics compared to equilibrium models.**

***Keywords*—Biomass, Catalyst, Gasifying agent, Sorbent**

I. INTRODUCTION

With the rapid growth in economy and industrialization, renewable energy sources like fossil fuels began to deplete at a faster rate. This results in global warming and climate change which is leading us to the verge of extinction.

Biomass can be used to meet the energy demands by biochemical as well as thermo chemical process. Among these thermo chemical conversion is more efficient and gasification is an example for this. Gasification is a thermo chemical process which converts carbonaceous materials into producer gas or chemical feedstock. Biomass is a renewable and eco friendly and carbon neutral source of energy [1].

Gasifier is the reactor in which gasification takes place. The different types of gasifiers available are fixed bed gasifier and fluidized bed gasifier. Of these fixed beds are classified into updraft, downdraft and cross draft gasifier. Fluidized bed gasifiers are classified into circulating fluidized bed and bubbling fluidized bed. Fluidized bed gasifier is most efficient because of its high heat transfer rates, load flexibility, fuel flexibility, moderate oxidation, steam requirements and high temperature throughout the gasifier [2].

Gasifying agents react with solid carbon and heavier hydrocarbons to convert them into low molecular weight gases like CO and H_2. The main gasifying agents used for gasification are air, steam and oxygen. A steam medium is preferred if high hydrogen content and higher heating value are required for syngas. But steam has its drawback as it results in higher tar content. When using the medium of air or oxygen it has gained popularity as the most practical gas production agent due to its low cost and availability.

However, the LHV of the product gas is quite low with air as gasifying agent due to the dilution of nitrogen [3].

The present paper deals with the review on experimental investigations and ASPEN Plus simulations of fluidized bed gasification. Here in experimental investigation we analyze the effect of gasifying agent, bed temperature, equivalence ratio, steam to biomass ratio, sorbent to biomass ratio, bed material and cleaning of syngas. In ASPEN Plus simulations we analyze equilibrium model, kinetic model and combined equilibrium and kinetic model.

II. EXPERIMENTAL INVESTIGATIONS

The parameters considered were SBR, ER, bed temperature, SOBR, bed material, types of biomass and gasifying agent. The aforementioned parameters were varied and the results were analyzed.

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A. Effect of SBR

Vazquez et al. [4] analyzed the effect of SBR with air and steam as the gasifying agent. Different SBR considered were 1, 0.33, 0.11, and 0.25. The results showed an N_2 free syngas composition. H_2 and CO_2 content was found to be increased whereas CO content decreased. Ismail et al. [5] analyzed the effect of SBR with air as the gasifying agent. Different SBR considered were 0, 0.25 and 0.5. A syngas with increased H_2 composition was obtained at an SBR of 0.5. But there was a significant reduction in CO and increase in CO_2. Kuo et al. [6] varied the SBR from 0 to 2 with air as the gasifying agent. Results showed that with increasing SBR, H_2 and CO_2 production increased but CO production decreased. Lin et al. [7] worked on an SBR of 0.5 with air as the gasifying agent. They found that H_2 and CO_2 production were increased, whereas CO production was decreased. Karl and Poll [8] varied the SBR between 0.7- 0.8 with steam as gasifying agent. The maximum gas yield observed was 1.4 g/Nm^3 at an SBR of 0.6. Song et al. [9] analyzed the effect of SBR from 0 to 0.4. Results showed that with increasing SBR, ash content was increased. Corella et al. [10] varied SBR from 0.2 to 2 with steam as the gasifying agent. Result showed that optimum SBR was found to be 0.28 were higher H_2 yield was observed. Ruoppolo et al. [11] analyzed the effect of SBR from 0.44 to 0.91 with steam as the gasifying agent. They found that at an SBR of 0.6, H_2 production was increased.

B. Effect of ER

Equivalence ratio is defined as the ratio of actual air-fuel ratio to the stoichiometric air-fuel ratio. Timmer and Brown [12] analyzed char transforming in a bubbling fluidized bed gasifier. They varied the ER from 0.2 to 0.3 and it was observed that better results were obtained at 800°C with an ER of 0.25. Minwin et al. [13] analyzed refuse paper and plastic fuel (RPF) and wood pellet gasification in a fluidized bed gasifier by varying equivalence ratio from 0.3 to 0.5 with air as gasifying agent. The concentration of CO increased with wood pellets and decreased with RPF when equivalence ratio was increased. The concentration of H_2 from RPF was lower than that from wood pellets and tar concentration decreased with increase in equivalence ratio. Arena and Gregorio [14] worked on solid waste gasification in a fluidized bed gasifier with air as gasifying agent. ER was varied from 0.24 to 0.39. Cold gas efficiency (CGE) ranging from 93 to 98% was obtained when ER was higher than 0.3. Singh et al. [15] dealt with gasification of ground nut shell in a bubbling fluidized bed gasifier with air as gasifying agent. They varied the ER from 0.29 to 0.32 and found out that at an ER of 0.31 the CGE was 71.8% and carbon conversion efficiency was 88%. Gas yield obtained was 1.84 to 2.15 Nm^{3}gas/kg. Kim et al. [16] worked on air gasification of wood pellets in a bubbling fluidized bed gasifier. The ER was varied from 0.19 to 0.27. Syngas composition was found to be increased when ER was decreased from 0.27 to 0.19. H_2 concentration increased from 14.5 to 16.5%, CO from 13.8 to 16.1% and CH_4 from 4 to 5.3%. Behainne and Martinoz [17] analyzed air gasification of rice husk in a pilot fluidized bed gasifier. ER was varied from 0.24 to 0.35 and at an ER of 0.24 a maximum LHV of 3.78 MJ/Nm^3 was obtained. Kulkarni et al. [18] dealt with torrified pine gasification in a bubbling fluidized bed gasifier. ER was selected as 0.20, 0.25 and 0.30 to study the effect on the contaminant yield. Results showed that ER has no significant effect on contaminant yield.

C. Effect of Bed Temperature

Bed temperature is a key factor in the formation of char, gas composition. Loha et al. [19] analyzed the effect of bed temperature in a fluidized bed gasifier with steam as gasifying agent. They found that the H_2 and CO composition increased from 50.50 to 54.40% and 14.3 to 18.5% respectively when temp was increased from 690 to770°C, whereas CO_2 and CH_4 decreased from 26.40 to 19.4% and 8.60 to 7.70% respectively. Kumar et al. [20] worked on the effect of the bed temperature in a fluidized bed gasifier with steam as gasifying agent. They found that the energy efficiency increased to 96% at a temperature of 850°C. Pfefeir et al. [21] analyzed the effect of the bed temperature in a dual fluidized bed gasifier with steam as gasifying agent. They found that the tar was reduced from 2 to .5 g/Nm^3 at a temperature of 820°C. Gil et al. [22] analyzed the effect of bed temperature in a fluidized bed gasifier (FBG) with air as gasifying agent. They found that that higher H_2 composition of 17%, CO composition of 28% and CH_4 composition of 5.2% was obtained at 840 °C. Lv et al. [23] worked on the effect of the bed temperature in a fluidized bed gasifier with air-steam as gasifying agent. They found that the temp of 900°C give better hydrogen yield of 71 H_2 /kg. Ismail et al. [24] studied the effect of the bed temperature in an FBG with steam as gasifying agent. They found an increase in CO_2 and H_2 production and decrease CO production at 750 °C compared to that at 850°C. Aghaalikhani et al. [25] analyzed the effect of the bed temperature in an FBG with steam as gasifying agent. They found that the H_2 composition was increased from 25-46% when temperature was increased from 650-900°C.

D. Effect of SOBR

Zhou et al. [26] analyzed the effect of CaO in an FBG with steam as gasifying agent. They found that tar decreased from the 5.07 g/Nm^3 to 6.88g/Nm^3 when SOBR was increased from 0 to 2. Savuto et al. [27] analyzed the effect

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of ceramic filter candle filled with nickel catalyst in FBG with steam as gasifying agent. They found that the quality of producer gas was increased and tar was reduced from 3 g/ Nm^3 to 2.5 mg/ Nm^3. H_2 content was increased from 40 to 50%. Rapagana et al. [28] analyzed the effect of CaO catalyst in FBG with steam as gasifying agent. They found out that lower tar residue was 0.45 and H_2 content was increased by 60%. Acharya et al.[29] analyzed the effect of CaO catalyst in FBG with steam as gasifying agent. They found that CO_2 content was decreased to 93.33%. Udomsorichahrom et al. [30] worked on the effect of CaO catalyst in FBG with steam as gasifying agent. They found that H_2 content was increased to 78% and tar and CO_2 content reduced to 4.9% and 2.48 g/Nm^3 respectively when CaO is used. Rapagana et al. [31] analyzed the effect of olivine particle as catalyst in FBG with steam as gasifying agent. They found that producer gas was increased by 50% and 20 fold reduction in tar. Char was reduced by 30%.

E. Effect of Bed Material

Tian et al. [32] analyzed the effect of different bed material limestone, calcinated dolomite, olivine with air as gasifying agent. They found that mole fraction of H_2 was 49.1% with dolomite bed material. The tar content was also reduced. Yang et al. [33] worked on the effect of the different bed material like quartz sand, olivine natural dolomite with steam as gasifying agent. They found that tar content was reduced to 39.2 g/Nm^3 when olivine is used as bed.

F. Effect of Different types of Biomass

Minwin et al. [34] analyzed the effect of different types of biomass such as refuse paper and plastic fuel (RPF) and wood biomass. They found that the concentration of CO was increased with wood pellets and decreased with RPF when ER was increased. The concentration of H_2 from RPF was lower than that from wood pellets. Azargohar et al. [35] worked on the effect of different biomass like petroleum coke (PC) and lignite coal (LC). They found that H_2 and CO_2 yield was increased when combination of PC and LC was used and LHV was also increased. Aznar et al. [36] dealt with the effect of different biomass like saw dust, coal and plastic. They found that a combination of 60% coal, 20% biomass and 20% plastic gives an H_2 content of 7 to 15%, CO of 10 to 20%, LHV of 4 to 8MJ/Mn^3, gasyield of 1.5 to 5Mn^3/Kg and char yield of 120 to 350 g/Kg. Ruppodo et al. [11] analyzed the effect of different biomass like wood pellets, biomass, plastic pellets and olivine husk. They found that the use of biomass or plastic pellet results better hydrogen concentration up to 32%.

G. Effect of Gasifying Agent

Mauerhofer et al. [37] analyzed the effect of 65% CO_2 and 35% steam as gasifying agent. They found that the H_2 and CO_2 content decreased and LHV was decreased from 12.7 to 9.2 MJ/m^3. Couto et al.[38] worked on the effect of O_2, air and steam as gasifying agents. They found that the H_2 and CO_2 concentration was increased when steam or CO_2 was used as gasifying agent.

III. ASPEN PLUS MODEL

Advanced System for Process Engineering (ASPEN Plus) is a software that will allow the user to build a process model and then simulate it using complex calculations [39]. For the effective analysis of biomass gasification, modeling and simulation provides a lot of idea and data which supports experimental analysis. Suitably chosen simulation models can reduce the time, as well as cost compared to tedious experimental task. Also, we can find out the optimum conditions from a range of values. Researchers have successfully used ASPEN Plus simulator to simulate gasification process. In this section equilibrium model, kinetic model and combined equilibrium and kinetic model are reviewed [40].

A. Equilibrium Model

Equilibrium models can be used when the reaction is fast or has sufficient time to reach equilibrium. Chemical equilibrium is the state in which the forward and backward reaction rates are equal. Equilibrium model predicts only the end reaction product distribution, but no information is provided about temporal and spatial variation. Feng et al. [41] analyzed the effect of temperature and SBR in syngas composition in an interconnected fluidized bed gasifier with steam as gasifying agent and pine sawdust as feedstock. They found that to achieve a high content of bio syngas of approximately 85%, the gasification temperature higher than 750°C and SBR of 0.6 was required. He et al. [42] studied tar cracking and steam reforming in dual fluidized bed gasification of wood pellets using steam as gasifying agent. The tar content decreased from 50g/m^3 at 750°C to 13g/m^3 at 900°C and char fraction from 22.5% to 11.5%. Hussain et al. [43] used ASPEN Plus to simulate palm kernel shell gasification in a pilot scale circulating fluidized bed gasifier with air and steam as gasifying agents. For a temperature range of 600°C to 675°C, H_2 content was increased from 79.92 to 82.4%, when SBR was increased from 1.5 to 2.5. Rao et al. [44] developed a simulation model for steam gasification of coffee, neem husk, green waste, feed waste, MSW, pine sawdust, wood chips etc. in a fluidized bed gasifier. They arrived at a conclusion that the CO conversion decreases with increase in Water Gas Shift (WGS) temperature ranging from 250 to 450°C. CO_2

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conversion increases with increase in reverse WGS temperature ranging from 450 to 900°C. Preciado et al. [45] analyzed steam – O_2 gasification of Colombian coal in a bubbling fluidized bed gasifier. The temperature range selected was 800 to 1000°C. The simulation result showed that the Rectisol process is an effective method for CO_2 and H_2S capture as these compound concentrations in the H_2 rich syngas were very low. Adnan and Hossain [46] worked on microalgal gasification in a fluidized bed reactor with steam and O_2 as gasifying agents. The highest H_2 concentration was observed in the S.almeriensis at 1 bar with SBR and ER ratio of 2 and 0.1 respectively. The corresponding GSE and CGE were found to be 0.49 and 0.85 respectively. The highest CGE was found in gasification of N.Oculata. Marcantonio et al. [47] analyzed air-steam gasification of Hazelnut shell in a circulating fluidized bed gasifier. The H_2 recovery ratio of this process, expressed as the ratio of H2 produced to the input biomass was 38%. After replacement of the Pressure Swing Adsorption (PSA) unit with the Palladium membrane, the H_2 recovery of the process increased to 49%. Optimum temperature range was 850°C. Acar and Boke [48] modeled steam gasification of almond shell in a bubbling fluidized bed gasifier. At an optimum SBR of 1.5, the temperature was varied from 650 to 1100°C which led to an increase in H_2 production and it reached the maximum value of 57.6% at 900°C. Motta et al. [49] analyzed sugarcane bagasse gasification in a circulating fluidized bed (CFB) gasifier with steam and O_2 as gasifying agents. They found that in 750 to 950 °C temperature range of steam only scenario CO content increased by 20.7% while CO2 decreased by 24.3%. The CFB steam blown gasifier was the most promising option for future synthesis purposes due to its higher H_2/CO ratio and higher dry syngas flow rates and CGE. Saha et al. [50] modeled a steady state equilibrium-based simulation model for gasification of carbonized cow manure in a fluidized bed gasifier with CO_2 as gasifying agent. Simulation results suggested a process temperature of 850°C and ER of 0.3 as the optimum condition for gasification of manure derived hydrochar in presence of CO_2 oxidizing agent. Hydrochar derived from hydrothermal treatment of cow manure at 260°C demonstrated the best performance in terms of syngas production and LHV. Alamina et al. [51] developed a lignocellulose gasification in a dual fluidized bed gasifier with steam and air as gasifying agents. Results showed that the H_2 and CO_2 contents in the product gas decreases with increasing temperature and SBR, while CO and CH_4 showed opposite trends. Mehrpaya et al. [52] dealt with air gasification of various biomasses like rice husk, peach stone, rice straw and corn cobb in a bubbling fluidized bed gasifier. Energy and exergy analysis along with related expressions development were done. The obtained results indicate that the maximum syngas energy efficiency refers to rice husk and peach stone biomasses. Camacho et al. [53] worked on air gasification of sugar cane in a circulating fluidized bed gasifier. Results showed that the CO_2 percentage in the syngas composition increases with ER; however the CO and H_2 percentage decreased. The higher temperature increases the percentage of CO, but decreases CO_2 and H_2. Doherty et al. [54] made a simulation model to analyze the effect of air preheating in sugarcane bagasse gasification in a circulating fluidized bed gasifier with air as gasifying agent. Gas heating value was found to decrease with increase in ER. Air preheating increases the H_2 and CO production, which in turn increases the gas heating value and CGE. Modeling and simulation of CO_2 capture in air–steam gasification of saw dust using ASPEN Plus process simulator was done by Rupesh et al. [55]. The proposed quasi-steady state model incorporates pyrolysis, tar cracking and char conversion using existing experimental data. Maximum H_2 mole fraction of 31.17% was obtained at a temperature of 900 K, ER of 0.25, and SBR and SOBR of unity. The H_2 and CO_2 mole fractions were found to be increased and decreased by 28.10% and 42.6%, respectively, when compared with the corresponding non- sorbent case.

B. Kinetic Model

In equilibrium model, the modeling is based on equilibrium principles whereas in kinetic model, modeling is done considering the reaction kinetics. Zhou et al. [26] worked on the simulation of biomass in a bubbling fluidized bed gasifier with steam as gasifying agent and used CaO as sorbent. Results showed that tar yield decreased from 15.07g/Nm^3 to 6.68g/Nm^3 with the increase in SBR from 0 to 2 and a slight increase in the H_2 yield was obtained as SBR increased from 1 to 1.5. Paul et al.[56] dealt with pine saw dust gasification in a bubbling fluidized bed gasifier with air and team as gasifying agent. Results showed that temperature has greatest overall influence on H_2 production. Hossein et al.[57] dealt with a semi kinetic model to study the catalytic behavior of CaO on gasification of rice husk, in a fluidized bed gasifier with air and steam as gasifying agent. Results showed that syngas yield and hydrogen decreased for ER from 0.15 to 0.25. Beheshti et al. [58] used wood pellets as biomass for gasification in a bubbling fluidize bed gasifier with air and steam as gasifying agent. With a decrease in biomass particle size, the concentration of CO, H_2 and CH_4 was increased.

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C. Combined Equilibrium and Kinetic Model

Here reaction kinetics as well as equilibrium principles are considered for reactor modeling and simulation. Atikah and Harun [59] dealt with micro algal gasification process in a circulating fluidized bed gasifier with air as gasifying agent. Highest H_2 concentration was found at a temperature of 660^{o}C and for CO and CH_4 the temperature was found to be 600^{o}C. Rasul et al. [60] used wood chips for gasification in a fluidized bed gasifier with steam as gasifying agent. Results showed that optimum air fuel ratio was 5. Sadhwani et al. [61] used wood chips for gasification in a fluidized bed with CO_2 as gasifying agent. Results showed that for temperature ranging from 700^{o}C to 995^{o}C model predicted values for CO and H_2 were close to experimental ones.

Suwatthikal et al. [62] dealt with gasification of lignocellulose biomass in a fluidized bed reactor with steam as gasifying agent. Optimum parameters obtained were temperature of 911^{o}C, ER of .18 and SBR of 1.78. Ahmed et al. [63] analyzed gasification of wood in a fluidized bed with air as gasifying agent. Tar cracking was considered here. This paper reviews different tar models in which tar was represented as different components such as naphthalene, toluene and even as bilk tar. Nikoo and Mahinpoy [64] dealt with the gasification of straw bagasse, husk and wood chips in a fluidized bed gasifier with air and steam as gasifying agents. Results showed that higher temperature improves the gasification process.

IV. CONCLUSIONS

With the help of the experimental setup a detailed study and analysis of different Gasification techniques can be observed. The effect of various parameters on the syngas composition is noted. This review is focused on study of fluidized bed gasifier. The present work helps in understanding the current advancement in this field and what further can be done to improve the process. The best operating conditions for best output can be understood by varying parameters like ER, SBR, bed temperature, gasifying agent, biomass, catalyst, sorbent etc. This information will be helpful for researchers by providing details for adopting a suitable model or for selecting a suitable gasifier for their specific application. The different types of ASPEN Plus models used for fluidized bed gasification of biomass are kinetic model, equilibrium model and combined kinetic and equilibrium model. Kinetic models predict the progress and product composition at different positions along a reactor whereas an equilibrium model predicts the maximum achievable yield of a desired product. Equilibrium models are easy to evaluate and find out the result. But kinetic models are very accurate compared to equilibrium model because they consider the reaction kinetics and reactor hydrodynamics.

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