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Fluidised Bed Gasification of Multiple Agricultural Biomass Derived Briquettes

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Abstract**—**Biomass briquette gasification is regarded as a promising route for efficient briquette use in energy generation, fuels and other useful chemicals. However, previous research has been focused on briquette gasification in fixed bed gasifiers such as updraft and downdraft gasifiers. Fluidised bed gasifier has the potential to be effectively sized to medium or large scale. This study investigated the use of fuel briquettes produced from blends of rice husks and corn cobs biomass, in a bubbling fluidised bed gasifier. The study adopted a combination of numerical equations and Aspen Plus simulation software, to predict the product gas (syngas) composition base on briquette density and biomass composition (blend ratio of rice husks to corn cobs). The Aspen Plus model was based on an experimentally validated model from the literature. The results based on a briquette size 32 mm diameter and relaxed density range of 500 to 650kg/m^3, indicated that fluidisation air required in the gasifier increased with increase in briquette density, and the fluidisation air showed to be the controlling factor compared with the actual air required for gasification of the biomass briquettes. The mass flowrate of CO_2 in the predicted syngas composition increased with an increase in air flow, in the gasifier, while CO decreased and H_2 was almost constant. The ratio of H_2 to CO for various blends of rice husks and corn cobs did not significantly change at the designed process air, but a significant difference of 1.0 was observed between 10/90 and 90/10 % blend of rice husks and corn cobs.

Keywords**—**Briquettes, fluidised bed, gasification, Aspen Plus, syngas.

I. INTRODUCTION

GASIFICATION is a thermochemical process used to convert carbon-based products such as biomass and coal into a gas mixture known as synthetic gas (syngas) which has various applications such as heat and electricity generation in gas turbine or generator engines, hydrogen production, Fischer Tropsch diesel, liquid synthesis and chemicals. Biomass gasification has been identified as a promising route for the utilisation of agricultural residues for energy generation. However, the low bulk density of loose agricultural residues can lead to increase requirement for storage space, increase cost of transportation, non-uniform feeding into the gasifier and inefficient thermal conversion of these residues. This has prompted the densification of loose biomass residues into briquettes and pellets of higher density prior to gasification.

Briquette application in gasification has attracted attention in recent years e.g. [16], [19], [22], but most of the work carried out so far on briquettes gasification has been focused on fixed bed gasifiers such as updraft and down draft gasfiers e.g. [22], [23]. Unlike the fixed bed fluidised bed gasifiers have the potential to be effectively sized to medium or large scale [17], [21]. This can be associated with the several benefits that fluidised bed possessed over fixed bed gasifiers such as better heat transfer between particles (gases and solids) as a result of intensive mixing in the bed, and the flexibility of fluidised bed gasifiers to changes in feed particle size.

A major drawback that may be encountered in fluidised bed gasification of biomass briquettes is the concentration of high-molecular-weight species (Tars). This may be attributed to increase in biomass feed particle size which occurs during the briquetting process. The increased particle size of feed biomass was reported to aid the formation of tars and polycyclic aromatic hydrocarbons (PAHs) [20], and CO_2 formation in the product gas [18], [20]. Tars are major impurities associated with biomass gasification syngas, which hinders the utilization of syngas [11].

Since the purpose of briquetting is to improve the bulk and energy density of loose biomass, it becomes imperative to investigate the implication of briquetting loose biomass prior to gasification.

The gasification model approach was adopted in this study because it helps account for the fundamental hydrodynamics of fluidisation and the gasification of solid materials. It also serves as a predictive tool which helps in the design, optimisation and scale-up of fluidised bed gasifiers [7].

The gasification simulation models can be grouped into four main categories including; Thermodynamic Equilibrium model, Kinetic model, Computational Fluid Dynamic (CFD) and the Artificial Neural Network. Unlike the equilibrium model, the kinetic model takes into account the gasifier geometry as well as its hydrodynamics [3]. The equilibrium and Kinetic approach have been utilised in many studies of the gasification process e.g. [4], [6], [9], [14].

Advanced System for Process ENgineering (Aspen) Plus is used to model and predict the performance of a process [1], [2], and this has found applications in the modelling and simulation of various gasification processes including, coal, plastic, rubbers, Polyethylene (PE) and biomass materials.

The fluidised bed gasification process has been modelled and simulated using ASPEN PLUS, to study and investigate the influence of various parameters of the gasification process and gasification products, for example, Begum [4], modelled

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and simulated the gasification of solid waste (wood) using ASPEN PLUS; Kannan [15] used ASPEN PLUS simulation to investigate the gasification of waste plastics; Nikoo & Maphinpey [9] used it to model sawdust gasification process, and addressed both hydrodynamic parameter and reaction kinetics.

For all the works carried out on fluidized bed gasification of solid biomass, the fuel briquettes has not been widely explored, and this is important with the increasing need for densification of biomass prior to gasification and the transition from small to large (commercial) scale biomass gasification process.

The specific objectives of this paper were to investigate the impact of fuel briquette density, material composition (blend ratio of rice husks to corn cobs) on the fluidisation velocity and gasification air requirement, and product syngas composition, using numerical equations and Aspen Plus simulation software.

II. MATERIALS AND METHODS

A. Briquettes Production

The biomass briquette data, used in the numerical equations and Aspen Plus simulation of the briquette gasification process, were original research data obtained from biomass briquette production in the laboratory from blends of rice husks and corn cobs, using a hand mold and hydraulic compression machine [8]. The produced briquettes were of 32 mm diameter, and density range of 490 to 650 kg/m^3 for 50/50 and 30/70 blends of rice husks to corn cobs. The proximate, ultimate and particle size properties of feed briquettes used for the gasification process, were obtained from literature [13], [12] and laboratory characterisation by [8].

B. Model Approach

The briquette gasification model was based on an experimentally validated model by [7] for gasification of olive kernel in a bubbling fluidised bed reactor, and it is referred to as the "BASE MODEL" in this study, while the new model in this study is referred to as the "CURRENT MODEL". The base model was experimentally validated by its authors, and the current study used the reported model to build an Aspen Plus model using briquette properties. This was carried out for the purpose of predicting the syngas composition from the fluidised gasification of multiple biomass derived briquettes, produced by [8].

C. Assumption

The following assumptions were considered for the gasification process of the current model and also according to the base model.

- The process is steady state and isothermal.
- Biomass devolatilisation is instantaneous and volatile products mainly consist of H_2, CO, CO_2, H_2O and CH_4.
- All gases are uniformly distributed within the emulsion phase.
- Feed particles are of uniform size and the average diameter remains constant during the gasification
- Char only contains carbon and ash.
- The simulation was performed using power-law kinetics.

The gasification process generally starts with drying of the biomass feed where water is driven off at temperatures above 100^{o}C, followed by pyrolysis (partial combustion) at temperatures between 300 and 500^{o}C, volatile combustion and char gasification usually above 800^{o}C, to give a mixture of gases (largely H_2 and CO) as the product stream. Fig. 1 shows a simple representation of biomass gasification in a fluidised bed.

Biomass fuel mainly consists of carbon, hydrogen, oxygen, nitrogen and sulphur. During the gasification process, in the combustion zone, carbon dioxide is formed from the carbon in the feed biomass and water (in the form of steam) is also obtained from the hydrogen present in the fuel biomass (1 and 2) [3], [7]. The products from the combustion zone including other partially cracked pyrolysis volatiles further passed through a bed of hot char where reduction reactions take place (3 to 4).

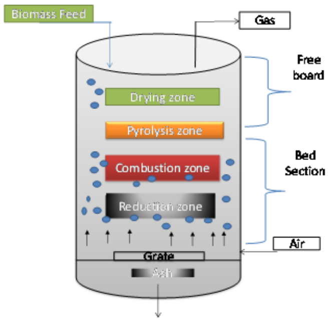

Fig. 1 A simple representation of different zones in biomass gasification process

III. REACTION KINETICS

Combustion Zone

$$C + \frac{1}{2}O_2 \rightarrow CO \tag{1}$$

$$C + O_2 = CO_2 \tag{2}$$

Reduction Zone

$$C + CO_2 = 2CO \tag{3}$$

$$C + H_2O = CO + H_2 \tag{4}$$

$$CO + H_2O = CO_2 + H_2 \tag{5}$$

$$C + 2H_2 = CH_4 \tag{6}$$

$$CO_2 + H_2 = CO + H_2O \tag{7}$$

IV. HYDRODYNAMICS

A. Assumptions

The following assumptions were considered in the calculation and simulation of the hydrodynamic parameters.

- The same reactor/gasifier dimension was assumed for all cases of briquette's density and composition.

- The fluidised bed is divided into two regions, bed and freeboard.
- The fluidisation state in the bed is maintained in the bubbling regime.
- The volume fraction of solids decreases with increasing height, similar to the grouping of bubbles in with solid particles returning to the bed.
- Gas velocity in the reactor is equal to the fluidisation velocity.
- Volumetric flow rate of gas increases with height corresponding to the production of gaseous products.
- Solid particles mixing consisting of char, ash and bed materials, are considered perfect.
- The reactor is divided into a finite number of equal elements with constant hydrodynamic parameters.
- The fluidised bed is one dimensional and any variation in conditions is considered to occur in axial direction.

The process parameters were calculated based on different briquettes density and composition (50/50 to 30/70 blend ratio of rice husks to corn cobs). To test the effect of only biomass composition on product gas composition, the blend ratio of rice husks to corn cobs was further varied between 90/10 and 10/90 rice husks to corn cobs.

1) Briquette Mass Flow

The briquette mass flow rate was calculated using (8) [3].

$$\mathrm{M_f} = \frac{Q}{LHV_{bm}\eta_{gef}} \tag{8}$$

2) Gasification Air Requirement

The gasification air as well as fluidisation air requirement were determined using (9) and (10).

$$M_a = m_{th}ER \tag{9}$$

The fluidisation air requirement was determined using (10) [3]:

$$f_a = \rho_{\mathrm{air}}\,\mu_{\mathrm{mf}}\,\mathrm{A_b} \tag{10}$$

According to [3], the minimum fluidisation velocity can be determined from (4).

$$\mu_{mf} = \frac{\mu}{d\rho}\,\text{Rế}_{mf} \tag{11}$$

V. ASPEN PLUS SIMULATION

Five different stages were considered in the Aspen Plus modelling and simulation of the briquette gasification process including drying, biomass decomposition, Volatile reactions, char gasification and gas-solid separation (Fig. *2*). Although a built-in model for customised fluidised bed gasification modelling was not available in Aspen Plus at the time of the Base Model, the software provided facility for user to input their own models using FORTRAN/Excel codes as well as reactions embedded within the input file [1], [2]. The following steps were used in the Aspen Plus model development [1], [2], and Fig. 2 shows the process flow sheet.

- Stream class specification and property method selection.
- System component specification (Aspen Plus data bank), and identifying conventional and non-conventional components.
- Defining the process flow sheet using unit operation blocks and connecting mass and energy streams.
- Specifying feed streams (composition, flowrate, thermodynamic condition).
- Specifying unit operation blocks (thermodynamic condition, chemical reaction).

Dry briquettes and ash were specified as non-conventional component in the Aspen Plus by using ultimate and proximate analysis of parent materials (rice husks and corn cobs) on a 50/50 blend ratio of rice husks to corn cobs, and referred to as the "base case" (Tables I-III).

TABLE I
RICE HUSKS AND CORN COBS 50/50 BLEND RATIO IN ULTIMATE ANALYSIS

Item	**Ratio**	**50/50 ULTANAL (%)**							
		ASH	**C**	**H**	**O**	**N**	**S**	**Cl**	**TOTAL**
RH	50%	7.2	21	2.5	19	0.1	0.0	0.0	50
CC	50%	0.5	24	2.7	22	0.2	0.0	0.0	50
	blend	7.7	45	5.2	40	0.3	0.1	0.0	100

The stream class in the Aspen Plus, was defined as MIXED, NC and PSD (MIXNCPSD) which indicates the presence of non-conventional solids and with particle size distribution. The enthalpy and density model for non-conventional components was selected as HCOALGEN and DCOALIGT.

TABLE II
RICE HUSKS AND CORN COBS 50/50 BLEND RATIO IN PROXIMATE ANALYSIS

Item	**Ratio**	**50/50 PROXANAL**					
		MC (%)	**F/C (%)**	**VM (%)**	**ASH (%)**	**HV (kj/kg)**	**Total**
RH	50%	4.1	10.7	32.1	7.19	8000	50
CC	50%	7.5	6.8	42.7	0.50	9000	50
	blend	11	17	74	7.2	17000	100

TABLE III
RICE HUSKS AND CORN COBS 50/50 BLEND RATIO IN SULFUR ANALYSIS

Item	**Ratio**	**50/50 SULFANAL**			
		Pyritic	**Sulfate**	**Organic**	**Total**
RH	50%	0.009	0.002	0.009	0.020
CC	50%	0.018	0.004	0.018	0.040
	blend	0.027	0.006	0.027	0.060

These are built-in Aspen Plus model for computing the heat of formation, heat of combustion and heat capacity of coal, while the density model DCOALIGT is used for computing the true density of coal on a dry basis using ultimate and sulphur analysis, and was adopted for the biomass materials.

The base model by [7] was slightly modified by removing the N and S separator situated before the RYIELD in the base model, and also by introducing the process air through the mixer instead of the RGIBBS (Fig. 2). The removal of the N and S separator was done to reduce the capital investment cost of the process since it was assumed that most of the N used in the drier (RSTOIC) went out with water in the Exhaust. Also, the introduction of air in the RGIBBS was observed to aid combustion of char before the RPFR in the briquette gasification.

A. Aspen Plus Gasification Flow Process

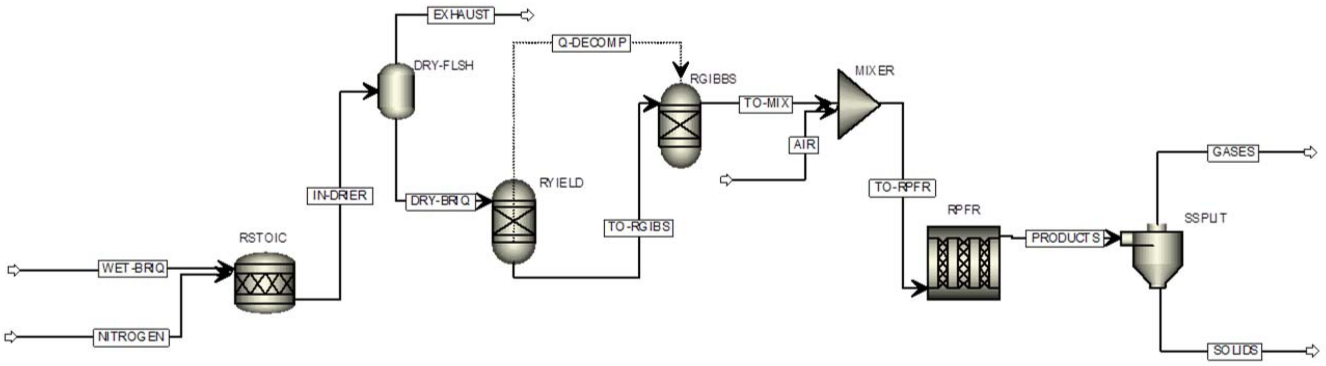

Fig. 2 Aspen Plus briquette gasification flow sheet

1) Briquettes Drying

The Aspen Plus stoichiometric reactor block (RSTOIC) was used to simulate the feed briquette drying process. The quantity of water removed from the briquettes was based on the proximate analysis of feed biomass which was determined by the blend ratio of rice husks to corn cobs. A calculator was attached to the RSTOIC in which an Aspen Plus provided FORTRAN CODE was used for the drying reaction. The mixture of dry briquette and gaseous water were separated using the separation column model DRY-FLSH. The dried feed briquettes were then moved into the next Aspen Plus block for decomposition process.

2) Briquette Decomposition

Briquettes feed decomposition process was simulated using the Aspen Plus yield reactor RYIELD. In this reactor, biomass material was converted into its constituent components including C, H_2, O_2, N_2, S and ash, by specifying the yield fraction of each component based on the biomass ultimate analysis.

3) Volatile Reactions

The Aspen Plus reactor block RGIBBS was used for the volatile reactions which uses the Gibbs free energy minimization to calculate the chemical equilibrium of the conventional components in the reactor. The RGIBBS does not require the user to specify reaction stoichiometry, and it automatically uses the temperature and pressure of the incoming feed (TO-RGIBBS) (Fig. 2), to establish the block and products exit temperature and pressure. In the RGIBBS, it was assumed that a small portion of the carbon that forms the gaseous phase, takes part in the volatile reactions, while the remaining solid phase char (carbon and ash) were moved to the RPFR for gasification reaction.

4) Char Gasification

The Aspen Plus block reactor RPFR was used to model the char gasification, a mixer was place before the RPFR where air for the gasification was introduced to mix with the products from RGIBBS. The char gasification was performed in the RPFR by specifying the gasification reactions and chemical kinetic. Similar to the base model, the hydrodynamic and kinetic parameters such as superficial velocity and voidage were kept constant.

5) Gas-Solid Separation

The separation of solid carbon and gas mixture was carried out using a CYCLONE SEPARATOR block in the Aspen Plus model. The final product consisting of mixture of gases received as main products of the gasification process. Other components of the product gas include Tars which were not considered in the current model. The gas was further scrubbed and dewatered.

VI. Results and Discussion

A. Effect of Briquette Density on Minimum Fluidisation Velocity and Air Requirement

Fig. 3 shows the effect of briquette density on the minimum fluidisation velocity, the fluidisation medium (air) required and the gasification air based on an equivalence ratio of 0.25 for air gasification (9). The minimum fluidization velocity (U_{mf}) is the point of transition between a fixed bed regime and a bubbling regime in a fluidized bed [10], it quantifies the drag force needed to attain solid suspension in the gas phase which makes it an important parameter in characterizing the hydrodynamics in the fluidised bed [5].

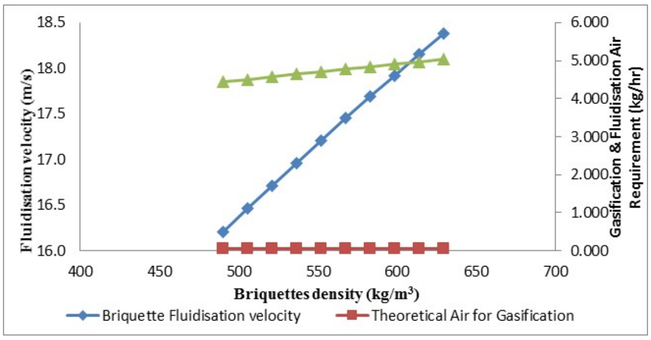

Fig. 3 Effect of briquette density on Umf and air requirement for fluidisation and gasification

From Fig. 4, the fluidisation velocity significantly increases with increasing briquette density with over 18 m/s of minimum fluidisation velocity required to transfer briquettes particles of 650 kg/m^3 into the bubbling phase in the reactor. This agrees well with findings from [5] using glass beads and wood chips. There is also an increase of air requirement for the level of fluidisation in the reactor as density of briquettes increase, which is consistent with expectation as well as findings presented by [24]. The gasification air is the actual air required for conversion of the solid biomass (gasification reaction kinetics), is significantly lower than the fluidisation air required. Since the gasification air is independent of the hydrodynamics in the reactor, it is not affected by the change in briquette density but varies with change in briquette composition. The result shows that, the fluidisation air is limiting in the current gasification process which implies excess air supply for the gasification reaction.

B. Effect of Process Air Flow on Product Gas Composition

Fig. 4 shows the mass flow rate (kg/hr) of the Aspen Plus predicted syngas composition versus the gasification process air flow in the range of 1 to 10 kg/hr. The air flow range was based on the designed air requirement of 4.5 kg/hr (Fig. 4), calculated for the minimum briquette density used in this study.

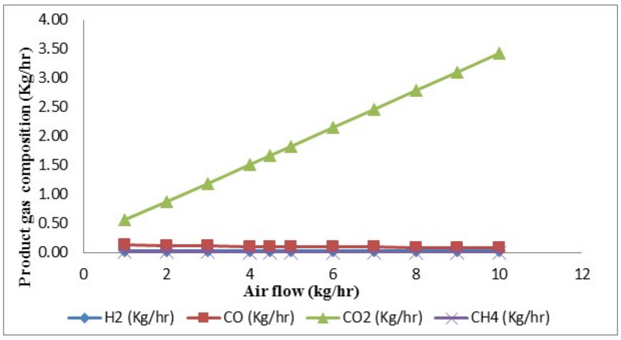

Fig. 5 Product gas composition at 50%RH/50%CC

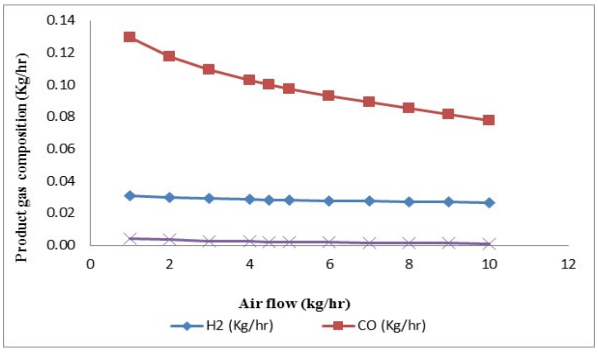

Fig. 6 Product gas composition at 50%RH/50%CC without CO_2

The CO formation decreases with increasing air flow which also resulted in increased CO_2 while CH_4 formation appears to be constant. The H_2 formation profile in the product gas initially increases but became constant with increased gasification process air supply. Ideally, the syngas should consist of mainly CO and H_2 in the appropriate ratio, and while this remains important, the syngas composition in Fig. 4 shows a reduction in quality of the syngas as process air supply increases which can be attributed to the increased oxidation reaction. Fig. 5 provides clear formation profiles of CO, H_2 and CH_4 in the absence of CO_2 in the product gas.

C. Effect of Airflow on H2/CO Ratio in Product Gas for Various Blends of Rice Husks and Corn Cobs

Fig. 6 shows the H_2/CO ratio for all the blends of rice husks to corn cobs briquettes considered in this study. From Fig. 6, the H_2/CO ratio increased with increase process air flow. The H_2/CO ratio at the design air of 4.5 (Fig. 3), was 0.3 which increased to about 0.6 at 16 kg/hr of air supply. The H_2/CO ratio for the briquette gasification is low compared with a recommended ratio of 0.5 to 1. The low H_2/CO ratio can be associated with a low H_2 formation in the gasification process which was almost constant as the process progresses. The increased H_2/CO ratio as air flow increases, was due to the increased formation of CO_2 as CO decreases. This highlights the requirement for optimisation of H_2 formation in briquette gasification process as well improve CO at an optimum air flow.

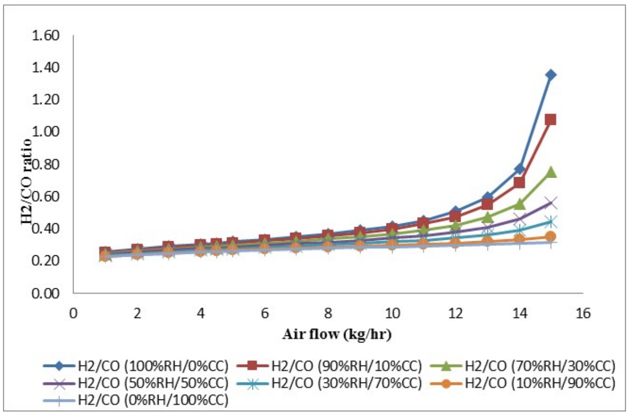

Fig. 7 H2/CO ratio for various blends of rice husks and corn cobs

The ratio of H_2 to CO for various blends of rice husks to corn cobs did not significantly vary even at the design air requirement, however, at higher air flow of 10 kg/hr, there was a significant difference between 100/0 and 0/100 ratio of rice husks to corncobs. The higher rice husks in the blend influenced higher H_2/CO ratio of up to 1.4 as air flow increased to 16 kg/hr. A reasonable ratio of 0.8 as reported by [7] was achieved at 70/30 blend ratio of rice husks to corn cobs.

D.Solid Composition in Briquette Gasification Product Stream for Various Blends of Rice Husks and Corn Cobs

Figs. 7 and 8 show the quantity of unreacted carbon and ash in the product stream from gasification of multiple biomass derived briquettes. The use of higher corn cobs in the blend resulted in increased quantity of residual carbon and reduced quantity of ash in the product stream, implying the high carbon and low ash content of the corn cob biomass (Table I).

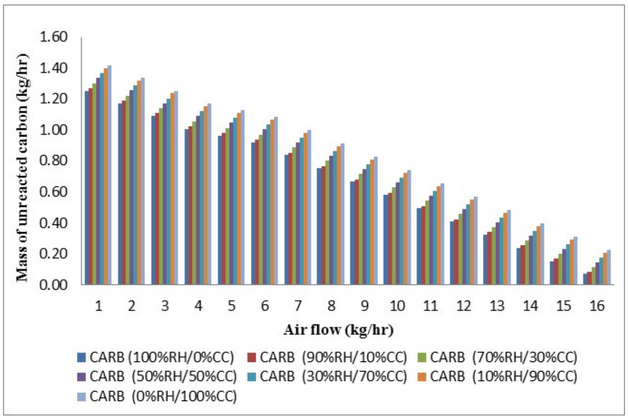

Fig. 8 Mass of unreacted carbon in product stream for various blends of rice husks and corn cobs with change in process air flow

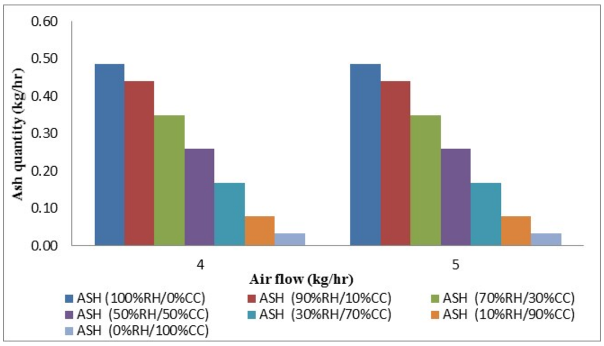

Fig. 9 Mass of ash in product stream for various blends of rice husks and corn cobs at design process air

VII. CONCLUSION

An investigation of the atmospheric fluidised bed gasification of multiple agricultural biomass briquette was carried out using numerical equations and Aspen Plus simulation. It was found that briquette density had significant impact on the fluidisation velocity and process air requirement. The quantity of CO and H_2 were low, and CO decreased with increased air supply in the gasifier, resulting in high CO_2 formation. Hydrogen was constant at above 3 kg/hr of air flow and 4.5 kg/hr feed briquette. The H_2/CO ratio was 0.3 at design process air and increased to 0.6 with an increase in the air flow. The blend ratio of rice husks and corn cobs did not significantly affect the H_2/CO ratio but at higher air flow, the H_2/CO ratio increased with higher ratio of rice husks in the blend. A good H_2/CO ratio of 0.8, was achieved at 70/30 % blend ratio of rice husks to corn cobs, at higher air flow. Briquette with higher blend ratio of rice husks also favored lower quantity of unreacted carbon but higher quantity of ash in the product stream. This implies the need for further understanding of biomass variability and hydrodynamic parameters on product composition from biomass briquette gasification.

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NOMENCLATURE

Q = Gasifier output
LHV_{bm} = Feed biomass heating value
$^{\eta}gef$ = Gasifier efficiency
m_{th} = Stoichiometric air required for complete combustion of biomass (0.1153C+0.3434(H-O/8)+0.0434S)
ER = Equivalence ratio (0.25 assumed for air gasification)
ρ_{air} = Density of gasification medium (air)
μ_{mf} = Minimum fluidisation velocity
A_b = Cross sectional area of bed
μ = Viscosity of fluidisation medium (air)
d = Particle diameter
$R\acute{e}_{mf}$ = Reynolds number at minimum fluidisation velocity
RH = Rice husks
CC = Corn cobs

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