ANALYTICAL AND EXPERIMENTAL STUDIES ON A 50 kWth DOWNDRAFT GASIFIER WITH BIOMASS BLENDS AVAILABLE IN THE HILLY REGIONS OF SOUTH INDIA

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***Abstract* — Biomass Gasification has emerged as the most promising technology for the decentralized heat and power applications. The prediction of the performance of biomass blends in gasifiers is an important area of study for the implementation of this technology in various applications, relevant to remote villages. This paper presents the theoretical and experimental studies conducted on a 50 kW$_{th}$ downdraft biomass gasifier with various combinations of the biomass materials such as wood, coconut shell, rubber seed kernel and coir pith, which are abundantly available in the villages of South India. Two zone kinetic equilibrium model is used for the theoretical simulation. The influence of equivalence ratio and composition of feedstock blends on the quality of producer gas and the conversion efficiency of gasifier were studied, and reported. The experimental and theoretical studies show that the effective utilization of biomass materials as blends can meet the rural energy demand.**

***Keywords*— kinetic model, equivalence ratio, gasifier, biomass blends, conversion efficiency.**

I. INTRODUCTION

With an emphasis on the need for alternative energy sources, many countries have started utilizing waste materials to form fuel sources. The energy obtained from biomass is the most viable technology to be used both for domestic and commercial applications. Different types of biomass materials are available all over the world as residues from the primary applications. The sources of these biomass materials are agriculture, timber logging, animal rearing, etc. In India, the energy from biomass dominates the rural energy consumption (Ravindranath *et al.*, 2005). Considering the concern over the importance and potential of biomass gasification process, in meeting the rural energy demand, it is necessary to model the gasification process, and predict the quality of producer gas to meet the requirements of different applications.

Among the gasification technologies, the downdraft gasification has an increased interest among the researchers worldwide due to its suitability to produce mechanical and electrical power at affordable price, even in small scale applications (Erlich and Fransson, 2011). Compared to other gasifier designs, the downdraft gasification is cheaper and produces relatively low tar (~0.1%) during gasification (Giltrap *et al.*, 2003). The simulation of gasifier can be carried out through thermodynamic equilibrium modeling, kinetic modeling, numerical modeling and artificial neural network (Budhathoki, 2013). The important parameters such as moisture content, equivalence ratio, producer gas composition and heating value of gas have been analyzed in the chemical equilibrium approach (Pitchandi, 2012; Melgar *et al.*, 2007).

The calorific value of the producer gas decreases with the increase in moisture content and gasification temperature (Zainal *et al.*, 2001). The model developed based on minimizing of Gibbs free energy is found to be appropriate to simulate the gasification process above 1500 K (Altafini *et al.*, 2003). Added to that, correction coefficient has been used to improve the accuracy of the equilibrium model (Jarungthammachote and Dutta, 2007).

Kinetic models are developed to predict the behavior of reduction zone. Wang and Kinoshita (1993) reported that the chemical reactions would proceed rapidly during the first 20 seconds of the residence time, and the increase in char particle size would decrease the surface reaction rate. A kinetic model incorporating char reactivity factor has been developed (Giltrap *et al.*, 2003) for analyzing the composition of gas along the reduction zone of a cylindrical downdraft biomass gasifier, in which the concentration of methane is over-predicted. Sharma (2008a) presented a model based on thermodynamic and chemical kinetics to find out the temperature and feedstock consumption rate in the pyrolysis zone. The study shows that the critical char bed length has to be maintained at 25cm for complete formation of product gas.

The experimental works have been carried out (Ahmed and Gupta, 2009; Erlich and Fransson, 2011; Jayah *et al.*, 2003; Jaojaruek *et al.*, 2011; Melgar *et al.*, 2007; Sheth and Babu, 2009; Singh *et al.*, 2006 and Singh *et al.*, 2014) to predict the influence of different factors like moisture content, equivalence ratio, reaction temperature and heating value of biomass on the performance of downdraft biomass gasifier. It is observed that the species concentration of combustible gases, gas production rate, conversion efficiency, etc., are high when ϕ is kept at 0.2 in a downdraft gasifier with woody biomass (Melgar *et al.*, 2007; Jarungthammachote and Dutta, 2007; Sharma, 2008b; Sheth and Babu, 2009 and Sheth and Babu, 2010).

Wander *et al.* (2004) have investigated the feasibility of using the residues from a saw mill as feedstock in a stratified downdraft gasifier. The gas generated after appropriate cleaning can be used to run internal combustion engine to meet the energy needs of the saw mill. The average values of global efficiency, cold gas efficiency and carbon conversion efficiency are found to be 69%, 60.04% and 93.58% respectively. It has been found that the higher efficiencies and higher temperatures are obtained in gas recirculation mode.

More importance has been given in previous works on the performance parameters of downdraft gasifiers working on fuels like cashew nut shell, pine wood, wheat straw, kiker wood, waste wood, food waste, card board, paper waste and pellets of palm oil residue. The numerical and experimental study conducted to analyze the behavior of reduction zone (Jayah *et al.*, 2003) shows that the conversion efficiency of the gasifier, with wood as fuel, decreases as the throat angle increases. The conversion efficiency was estimated as 56% for a moisture content of 15% and the optimum size of the biomass particle (wood chip) is 3 cm. Moreover, the optimum length of the reduction zone has been reported as 22 cm.

Many authors have emphasized the analysis of the gasification process and gasifier performance rather than the utilization of the available feedstock materials. The use of single biomass in a gasifier functioning throughout the year runs the risks of transportation, availability of the particular biomass throughout the year and complete utilization of various biomass materials available in a region (Buragohain *et al.*, 2011). Therefore mixing of biomasses in a gasifier could improve the continuous and steady operation of biomass gasifiers in remote areas. A model developed for a mixture of saw dust and cow dung in a downdraft gasifier shows that the mixing of cow dung would reduce the gas production rate and heating value. However, adding cow dung in the mixture by 40-50 % by mass would result in an overall fuel economy (Roy *et al.*, 2010). The studies on the feasibility of mixtures of particle type biomasses such as rice husk, bamboo dust and saw dust with a moisture content of 10%, show that the optimum air ratio of 0.3 and gasification temperature of 1073K have to be maintained in fluidized bed biomass gasifiers for a good decentralized power generation (Buragohain, *et al.*, 2011). In air gasification, the quality and quantity of producer gas varies widely depending on the gasifier configuration, equivalence ratio and feedstock properties such as chemical composition, moisture content, particle size, and density (Sheth and Babu, 2010). Therefore specific studies are needed to predict the performance of gasifiers when the above said parameters vary from place to place.

In this paper, analytical and experimental methods have been used to study the performance of downdraft gasifier with binary mixtures of biomasses such as wood, coconut shell, rubber seed kernel and coir pith. These materials have competitive physical characteristics, low cost and abundant availability in southern part of India, as by-products or residues from other applications.

To conduct the theoretical and experimental studies, samples of biomasses have been collected from various regions like places close to forest, coconut tree farms, sea shores and villages in remote areas. The binary mixtures of different proportions of feedstock considered are 90:10, 70:30, and 60:40. However, experimental study was conducted on selected blends in order to prove the validity of this approach. Based on the availability and performance, optimum mixture compositions are proposed. The gas generated from this approach can be used for local power generation and vapor absorption refrigeration based food preservation.

II. MATHEMATICAL MODEL

The schematic diagram of the gasifier model used in this study is shown in Fig. 1. It consists of an imbert type downdraft gasifier with uniform circular cross section at the top, varying cross section along pyrolysis and oxidation zones and cylindrical section at the reduction zone. The size of the gasifier is shown in Table 3. The drying, pyrolysis and oxidization zones are defined as zone-1 and thermodynamic equilibrium approach is used to model this zone. The reduction zone has been defined as zone-2 and it is modeled on chemical kinetics of char reactions. The biomass feedstock enters the gasifier at the top of the gasifier and moves downwards. The air is supplied at the combustion zone through the air tuyers inclined at 450 and the gas generated in the gasifier moves downwards and comes out at the bottom of the gasifier. The objective of the model is to predict the performance parameters like species concentration, gas production rate, temperature, HHV and gasifier conversion efficiency.

In order to implement the equilibrium analysis based on the previous studies (Wang and Kinoshita, 1993; Melgar *et al.*, 2007; Jarungthammachote and Dutta, 2007; Sharma, 2008b and Roy *et al.*, 2010), the assumptions used in this study are, composition of feedstock material on dry and ash free basis, steady state gas flow

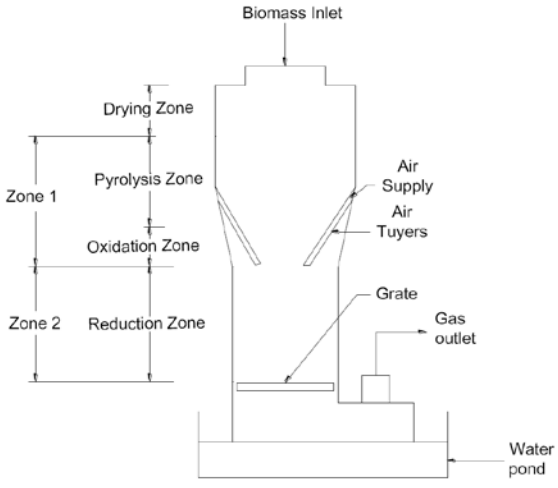

Fig. 1. Schematic of downdraft gasifier

inside the gasifier, adiabatic gasifier wall, sufficient time for all the reactions to take place, uniform species temperature at each level of gasification, negligible amount of tar or unburnt hydrocarbon in the exhaust, and the major species available in the producer gas are CO, CO_2, H_2, CH_4, and N_2.

A. Zone-1(Pyrolysis & Oxidation)

While using two different biomass energy sources, the mole fraction of the second biomass can be defined as *b* and the global reaction of gasification process for the mixture can be written as,

$$CH_lO_pN_q + bCH_tO_uN_v + M_wH_2O + X_g(O_2 + 3.76N_2) \rightarrow x_1CO + x_2H_2 + x_3CO_2 + x_4H_2O + x_5CH_4 + x_6N_2 + x_7C. \quad (1)$$

The representative chemical formulae ($CH_lO_pN_q$, $CH_tO_uN_v$) of different biomasses are de-rived from their ultimate analysis, using the generalized procedure (Melgar *et al.*, 2007). The number of moles of second biomass (*b*) depends on the proportion of the two fuels in the mixture and is given as (Roy *et al.*, 2010),

$$b = \frac{(1-0.01S)(1-0.01A_2)M_{C,1}}{0.01S(1-0.01A_1)M_{C,2}}. \quad (2)$$

The equations used for calculating the moles of oxygen in air (X_g) and moisture (M_w) have been taken from published literature (Roy *et al.*, 2010). The results of ultimate analysis of feedstock materials are shown in Table 1. The higher heating values of the feedstock materials are calculated using the Friedl's equation (Vaezi *et al.*, 2008).

$$HHV\left(\frac{MJ}{kg}\right) = 3.55C^2 - 232C - 2230H + 51.2CH + 131N + 20600. \quad (3)$$

The water gas shift and methanation reactions take place in zone-1are,

$$CO + H_2O \Leftrightarrow CO_2 + H_2. \quad (4)$$

$$C + 2H_2 \Leftrightarrow CH_4. \quad (5)$$

The ratio of rate constants for the forward and reverse reactions is the equilibrium constant (Basu, 2010). The equilibrium constants for these reactions depend on the temperature, partial pressure and moles of the respective species, and they are obtained as follows,

$$K_1 = \frac{(P_{CO_2}/P_O)(P_{H_2}/P_O)}{(P_{CO}/P_O)} = \frac{x_2x_3}{x_1x_4}. \quad (6)$$

$$K_2 = \frac{(P_{CH_4}/P_O)}{(P_{H_2}/P_O)^2} = \frac{x_5}{x_2^2}\left(\sum_{i=1}^{6} x_i\right). \quad (7)$$

The equilibrium constants K_1 and K_2 can be calculated from the changes in Gibbs free energy between the products and reactants:

Table 1. Ultimate analysis results of feedstock materials (DAF Basis)

Feedstock	C % Wt.	H % Wt.	O % Wt.	N % Wt.	S % Wt.
Wood Waste	45	6.28	40.51	0.42	0.057
Coconut Shell	50.2	5.7	43.4	0	0
Rubber seed kernel	43.21	6.0	50.25	0.55	0
Coir Pith	44	4.7	43.4	0.7	0

$$K_1 = \exp\left[-\left(g_{CO_2} + g_{H_2} - g_{CO} - g_{H_2O}\right)/RT\right], \quad (8)$$

$$K_2 = \exp\left[-\left(g_{CH_4} - 2g_{H_2}\right)/RT\right]. \quad (9)$$

The values of heat of formation and Gibbs free energy for different gases have been obtained from the JANAF Tables (Chase, 1986). The quantity of char generated from the gasification process is obtained from the fixed carbon data which is taken from the proximate analysis. The char is splitted into solid carbon and methane at the outlet of zone-1. Therefore, the equation is taken as

$$x_5 + x_7 = \frac{F_{C,1}}{C_1} + b\frac{F_{C,2}}{C_2}. \quad (10)$$

The number of moles of respective species, x_1 to x_7 formed in the gasification process has been calculated from Eqs. 1, 8, 9 and 10. A uniform temperature, throughout the horizontal section of the gasifier has been assumed to the species at the outlet of zone-1, and the same is determined from the energy balance across the zone considering that there is negligible amount of kinetic and potential energy changes.

The energy balance equation is defined as

$$Q_{in} + Q_{loss} = Q_{out}. \quad (11)$$

where Q_{loss} is the quantity of heat lost from the gasifier to the surrounding. Since the process is assumed to be adiabatic, Q_{loss} is taken as zero.

Based on the global reaction given in Eq. 1, the energy balance equation is expanded as,

$$H_{f,1} + bH_{f,2} + X_g\int_{T_0}^{T_a} C_{p,O_2}dT + 3.76X_g\int_{T_0}^{T_a} C_{p,N_2}dT + M_wh_{f,H_2O} + Q_{loss} = \sum_{i=1}^{6} x_i\left[h_{f,i} + \int_{T_0}^{T_a} C_{p,i}dT\right] + x_7C_{p,C}(T - T_0) + m_{ash}C_{p,ash}(T - T_0). \quad (12)$$

The energy carried out by individual species (*CO*, H_2, CO_2, H_2O, CH_4 and N_2), char and ash are considered separately in the above equation. Standard equations are used to find the heat of formation of fuels (Zainal *et al.*, 2001) and the specific heat of gaseous species. The specific heat of ash and char are taken as 840 J/kgK and 21.86 J/ molK respectively.

B. Zone-2 (reduction zone)

The species formed in the zone-1 enter the zone-2 and undergo the following endothermic reactions to form the final composition of the producer gas (Wang and Kinoshita, 1993; Giltrap *et al.*, 2003).

$$C + CO_2 \Leftrightarrow 2CO. \quad (13)$$

$$C + 2H_2O \Leftrightarrow CO + H_2. \quad (14)$$

$$C + 2H_2 \Leftrightarrow CH_4. \quad (15)$$

$$CH_4 + H_2O \Leftrightarrow CO + 3H_2. \quad (16)$$

The equilibrium constant (K_R) for the above four reduction reactions have been obtained from the following relations:

$$K_{R1} = \exp\left[-\left(2g_{CO} - g_{CO_2}\right)/RT\right], \quad (17)$$

$$K_{R2} = \exp\left[-\left(g_{CO} + g_{H_2} - g_{H_2O}\right)/RT\right], \quad (18)$$

$$K_{R3} = \exp\left[-\left(g_{CH_4} - 2g_{H_2}\right)/RT\right], \quad (19)$$

$$K_{R4} = \exp\left[-\left(g_{CO} + 3g_{H_2} - g_{CH_4} - g_{H_2O}\right)/RT\right]. \quad (20)$$

The above equations are assumed to be reversible and the rate of reaction is calculated using Arrhenius type kinetic rate equations (Roy *et al.*, 2010). The specific rates of reaction of the above equations are given by,

$$\tau_{R1} = C_{RF} A_{R1} \exp\left(\frac{-E_{R_1}}{RT}\right)\left(Y_{CO_2} - \frac{Y_{CO}^2}{K_{R1}}\right), \quad (21)$$

$$\tau_{R2} = C_{RF} A_{R2} \exp\left(\frac{-E_{R_2}}{RT}\right)\left(Y_{H_2O} - \frac{Y_{CO}Y_{H_2}}{K_{R2}}\right), \quad (22)$$

$$\tau_{R3} = C_{RF} A_{R3} \exp\left(\frac{-E_{R_3}}{RT}\right)\left(Y_{H_2}^2 - \frac{Y_{CH4}}{K_{R3}}\right), \quad (23)$$

$$\tau_{R4} = C_{RF} A_{R4} \exp\left(\frac{-E_{R_4}}{RT}\right)\left(Y_{H_2O}Y_{CH4} - \frac{Y_{H_2}^2 Y_{CO}}{K_{R4}}\right). \quad (24)$$

The values of these kinetic parameters, A_R and E_R for the forward reactions are taken from literature (Wang and Kinoshita, 1993). The specific reaction rates of the reverse reactions are evaluated from that of forward reactions and the equilibrium constants of the reactions. CRF in the rate of reaction is the char reactivity factor; represent the active site present in the char surface and the value of CRF lies between 1 and 10,000 (Sheth and Babu, 2009).

The mass flow rate of the species (i=1 to 7) at the inlet of the reduction zone depends on the feed rate of biomass (M_f), and it is expressed as

$$X_i^0 = \frac{M_f(0.01S)(1-0.01A_1)}{M_{C,1}} x_i; \quad i = 1,\ldots,7 \cdot \quad (25)$$

The rate of formation of a species i at any elemental control volume k is given by,

$$X_i^k = X_i^{k-1} + R_i^k \Delta V_k \cdot \quad (26)$$

where X_i^{k-1} is the rate of formation of species at the control volume, k-1. R_i^k is the net rate of formation of species, i and ΔV_k is the elemental control volume assumed in the reduction zone (Roy *et al.*, 2010) and it is obtained by,

$$\Delta V_k = \frac{\pi}{3}\left(r_k^2 + r_{k-1}^2 + r_k r_{k-1}\right)\Delta H \cdot \quad (27)$$

where, r_k and $r_{k-1}$are the values for the radii at the kth and k-1th sections of the reduction zone respectively. This is the generalized equation for the reduction zone control volume which has tapered conical section. Since the reduction zone is cylindrical, the values for these radii are equal. The energy balance across any control volume (k) in zone-2 is given as,

$$\sum_{i=1}^{6} X_i^{k-1}\left(h_{f,i} + \int_{T_0}^{T^{k-1}} C_{p,i}dT\right) + X_7^{k-1}C_{p,C}(T^{k-1} - T_0) + m_{ash}C_{p,ash}(T^{k-1} - T_0) = \sum_{i=1}^{6} X_i^{k}\left(h_{f,i} + \int_{T_0}^{T^{k}} C_{p,i}dT\right) + X_7^{k}C_{p,C}(T^{k} - T_0) + m_{ash}C_{p,ash}(T^{k} - T_0). \quad (28)$$

The temperature of the species within the control volume has been calculated by solving the Eq. (28). The concentration and temperature of species at the outlet of the last control volume are the conditions of the producer gas at the exit of the gasifier. The quality of the producer gas is evaluated in terms of the production rate of combustible gases, its heating value and temperature. The performance of the gasifier is evaluated in terms of conversion efficiency, which is defined as the ratio of energy content of the producer gas to the energy content of the biomass feedstock.

The equivalence ratio plays a vital role on the performance of the gasifier (Basu, 2010) and it is defined as,

$$\phi = \frac{(Air/Fuel)_{actual}}{(Air/Fuel)_{Stoichiometric}} \cdot \quad (29)$$

If the equivalence ratio is below 0.2, the conversion efficiency and gas production rate reduces drastically (Ahmed and Gupta, 2009). Therefore in this analysis, the equivalence ratio has been taken to be between 0.2 and 0.45, and the variations in performance parameters are studied. The higher heating value of the producer gas can be obtained by,

$$HHV_g = Y_{CO}HHV_{CO} + Y_{H_2}HHV_{H_2} + Y_{CH_4}HHV_{CH_4} \cdot \quad (30)$$

The blends used in this study and their combinations of biomass materials are given in Table 2.

III. EXPERIMENTAL SETUP

The schematic diagram of the experimental setup consists of an imbert downdraft biomass gasifier with the capacity of 50 kW_{th} and scrubber with cyclone separator and filters is shown in Fig. 2. The gasifier has been procured from standard supplier and the other components in the experimental setup have been built up by the research team. A gas analyzer is used to check the quality of the producer gas. A gas flow meter (type:

Table 2. Different types of blends of biomass materials

Feedstock Combination		Mole Fraction Ratio	Blend Symbol
Primary Energy Source	Secondary Energy Source		
Coconut Shell	Coir Pith	100:0	A0
		90:10	A1
		70:30	A2
		60:40	A3
Wood	Rubber Seed Kernel	100:0	B0
		90:10	B1
		70:30	B2
		60:40	B3
Wood	Coir Pith	100:0	C0
		90:10	C1
		70:30	C2
		60:40	C3
Coconut Shell	Rubber Seed Kernel	100:0	D0
		90:10	D1
		70:30	D2
		60:40	D3
Rubber Seed Kernel	Coir Pith	100:0	E0
		90:10	E1
		70:30	E2
		60:40	E3
Wood	Coconut Shell	100:0	F0
		90:10	F1
		70:30	F2
		60:40	F3

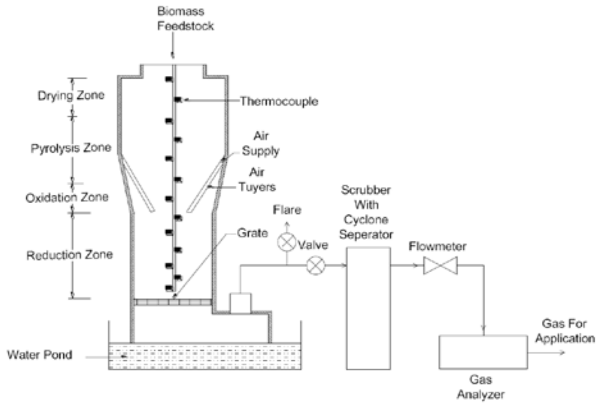

Fig. 2. Schematic diagram of the experimental setup of the downdraft gasifier

Table 3. Details of Gasifier

Parameter	Details
Type of gasifier	Downdraft Gasifier
Geometrical Parameters	OD: 925 mm(Pyrolysis Zone), 775mm (Reduction Zone); Total Height :2050 mm
Heating Type	Manual Ignition
Cooling Medium	Water
Feedstock Capacity	20-30 kg / h (depending on the type of fuel)
Feeding Equipment	Manual Feed
Gasifying Agents	Air
Operating Temperature	30- 1650 ºC
Feedstock	Wood Waste, Coconut Shell, Rubber Seed Kernel and Coir-pith

thermal flow meter, measuring range: 0-50 m^3/h, accuracy- ± 0.5%) is used to check the quantity of the gas generated. Air tuyers inclined at an angle of 45º to the horizontal are placed around the circumference of the oxidation zone. U-tube manometer is used to measure the flow rate of air. The Table 3 shows the details of the gasifier used in the experiment.

Calibrated K-type (chromel-alumel) thermocouples are placed in different locations to measure the temperature along the pyrolysis, oxidation and reduction zones. In order to avoid the heat loss, the gasifier wall is insulated internally with refractory fire clay. In this gasifier, both biomass feedstock and producer gas move downward as the reaction proceeds. To prevent the leakage of producer gas, the water tray is placed under the reactor.

Special arrangement is made to measure the flow rate of feedstock. The mesh used in the grate is selected based on the size of the feedstock material.

The biomass fuel enters through the door and flows down, gets dried and pyrolysed before being partially combusted by the gasifying media (air) entering at the air tuyers. The throat allows maximum mixing of gases in high temperature region, which aids tar cracking. Below the constriction or 'throat' the combustion gases along with tar pass through the hot char bed and are reduced to primarily CO and H_2.

A. Experimental Procedure

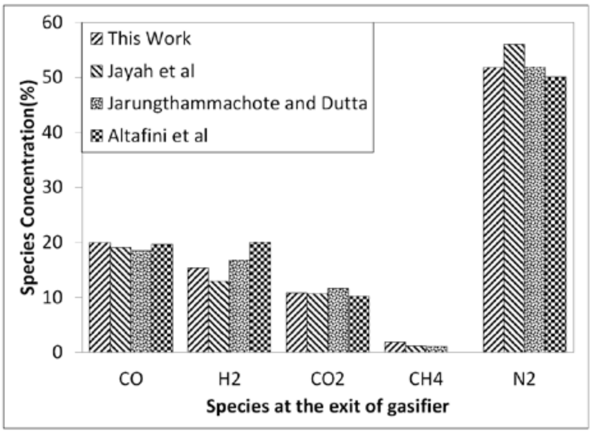

Fig. 3. Comparison of predicted and reported species concentrations at the gasifier outlet

To maintain a homogeneous mixture of biomasses, the blends were prepared in separate container and fed into the gasifier manually and the door was closed. The water tray was filled with sufficient water. Then air was supplied by the air blower and the biomass was ignited by dropping the red hot charcoal pieces into the gasifier through the opening in the air tuyers and air tuyers are then closed. The particle type material (coir pith) was briquetted to the size equal to the other materials. A metering rod having a flat plate at the bottom is kept on the feedstock to measure the mass flow rate. A data logger was used to record the temperature. Samples of the gas were taken every 10 minutes to analyze the composition in gas chromatograph. In addition to that, an online gas analyzer and a gas flow meter were used to measure the quality and quantity of output gas. Each blend was analyzed a minimum of three times, and the average values were taken. The air flow rate was measured by manometer. HHV and moisture content of feed-stock materials were checked before every loading and added to that hot air drying was used to maintain the moisture content.

Each experimental run has been continued for about 5- 6 hours. However a stable operation was observed for duration of 4 hours. The measurements were taken when the operation was stable. Once the gas quality reduces, necessary measures were taken to shut off the gasifier as per the manufacturer's guidelines.

IV. RESULTS AND DISCUSSION

The results obtained from analytical and experimental studies have been analyzed, and the influence of the mass fraction of various components on the performance parameters such as species concentration, gas production rate, HHV of producer gas and conversion efficiency were evaluated. Since equivalence ratio plays a major role on the quality and quantity of producer gas, the variation of performance parameters for the equivalence ratio between 0.2 and 0.45 has been analyzed. The comparison of species concentration obtained from the present study has been made with the previous works (Altafini *et al*., 2003; Jarungthammachote and Dutta, 2007; and Jayah *et al.*, 2003) and shown in Fig. 3 the detail of operating conditions at which the previous works were carried out is also given in Table 4. It shows that the deviation of present result is within 12%. Therefore this model can be used to predict the species concentration, gas production rate, HHV and conversion efficiency.

Table 4. Operating Conditions considered for Model Validation

Reported Study	Operating Condition
Altafini *et al.*	Downdraft gasifier, modeled based on chemical equilibrium, feedstock - saw dust with 20% moisture con-tent and A/F Ratio 1.86
Jarungthammachote and Dutta	Downdraft gasifier, modeled based on thermodynamic equilibrium, feedstock- MSW with 16% moisture content and equivalence ratio 0.44
Jayah et al.	Downdraft gasifier, modeled based on computer simulation, feedstock-MSW with 14.7% moisture content and A/F Ratio 1.86
Present Work	Downdraft gasifier, modeled based on two-zone kinetic equilibrium, feestock- blends of coconut shell, wood, rubber seed kernel and coir-pith with 10% moisture content and equivalence ratio 0.2

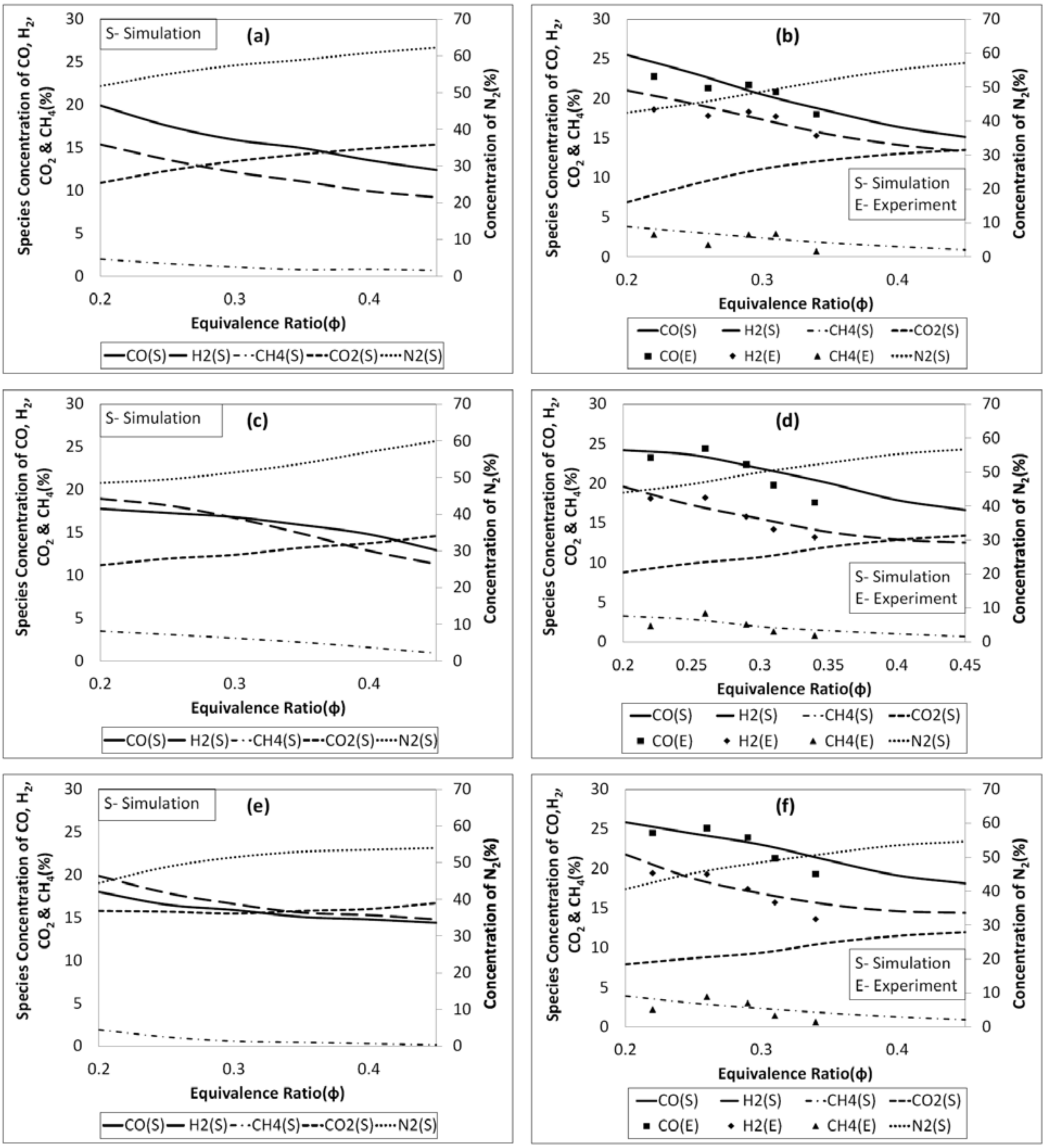

Fig. 4. Variation of species concentration with ϕ for the blends with 90:10 composition of (a) Coconut Shell: Coir Pith (b) Wood: Rubber Seed Kernel (c) Wood: Coir Pith (d) Coconut Shell: Rubber Seed Kernel (e) Rubber Seed Kernel: Coir Pith (f) Wood: Coconut Shell

A. Species Concentration

The quality of the producer gas depends on the concentration of the combustible gases such as *CO*, H_2 and CH_4 at the exit of the gasifier. Even though the theoretical analysis was carried out for all the blends given in Table 3, only a few blends with 90:10 composition are considered for discussion. Figure 4 shows the variation of species concentration with respect to equivalence ratio for the blends A1, B1, C1, D1, E1 and F1. It is observed that the species concentration of combustible gases is high when ϕ is kept at 0.2 (Sheth and Babu, 2009).

Therefore, the airflow rate should be adjusted to maintain the equivalence ratio close to 0.2 for all the feedstock materials.

Since the coir-pith has given a comparatively poor performance (Singh *et al.*, 2014), the variation of species concentration for the blends with coir-pith has not been studied experimentally. The concentration of combustible species (*CO*, H_2 and CH_4) obtained from the experimental study for the blends B1, D1 and F1 are depicted in Fig.4b, Fig.4d and Fig. 4f. The trend is similar to that obtained in the simulation. Furthermore the trend is also similar to the previous studies (Roy *et al*., 2013, Sheth and Babu, 2009 and Wang and Kinoshita,

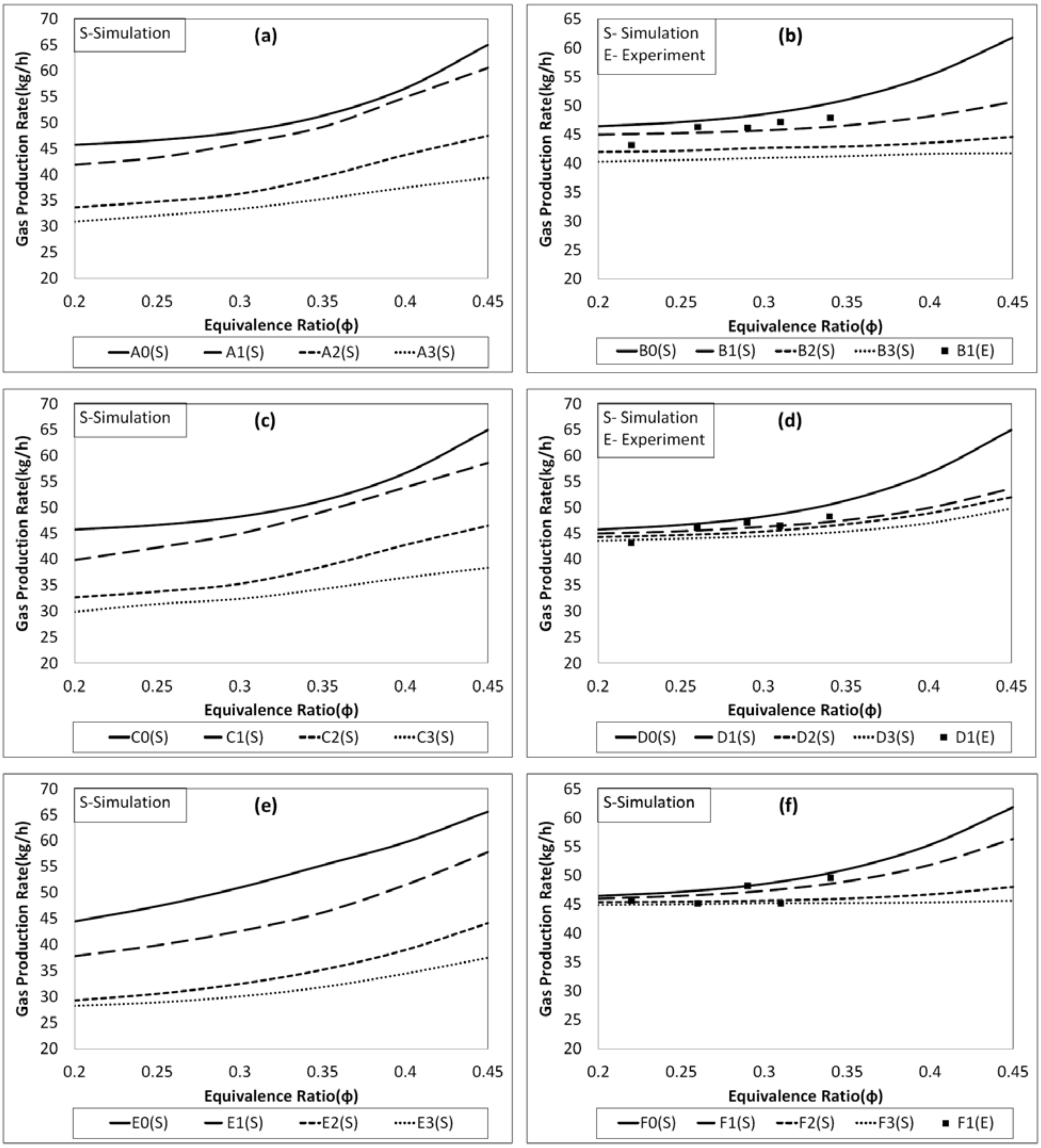

Fig. 5. Variation of gas production rate with ϕ for the blends, (a) Coconut Shell: Coir Pith. (b) Wood: Rubber Seed Kernel. (c) Wood: Coir Pith. (d) Coconut Shell: Rubber Seed Kernel. (e) Rubber Seed Ker-nel: Coir Pith. (f) Wood: Coconut Shell**.**

1993). However, due to the heat transfer that takes place across gasifier walls and non-uniform flow patterns prevailing in-side the gasifier, the results obtained from simulation are deviating 10-15% from the experimental values.

Among the blends, the combinations of wood, coconut shell and rubber seed kernel show a higher concentration of CO and H_2. However, the best species concentration is observed in wood and coconut shell combination (Fig. 4f).

B. Gas Production Rate

The gas production rate is influenced by the equivalence ratio. Therefore it has been analyzed and plotted in Fig. 5. Even though the combustible gas composition decreases due to increase in ϕ (Fig. 4), an increase in gas production rate is observed. This is caused by the high concentration of non-combustible gases in the producer gas. When the quantity of O_2 increases, the combustion reactions will dominate and the production of CO, and H_2 could be reduced. Therefore the concentration of combustible gases is reduced with the increase in equivalence ratio.

For the blends of wood, coconut shell and rubber seed kernel, it is observed that the variation in gas production is not significant until the equivalence ratio

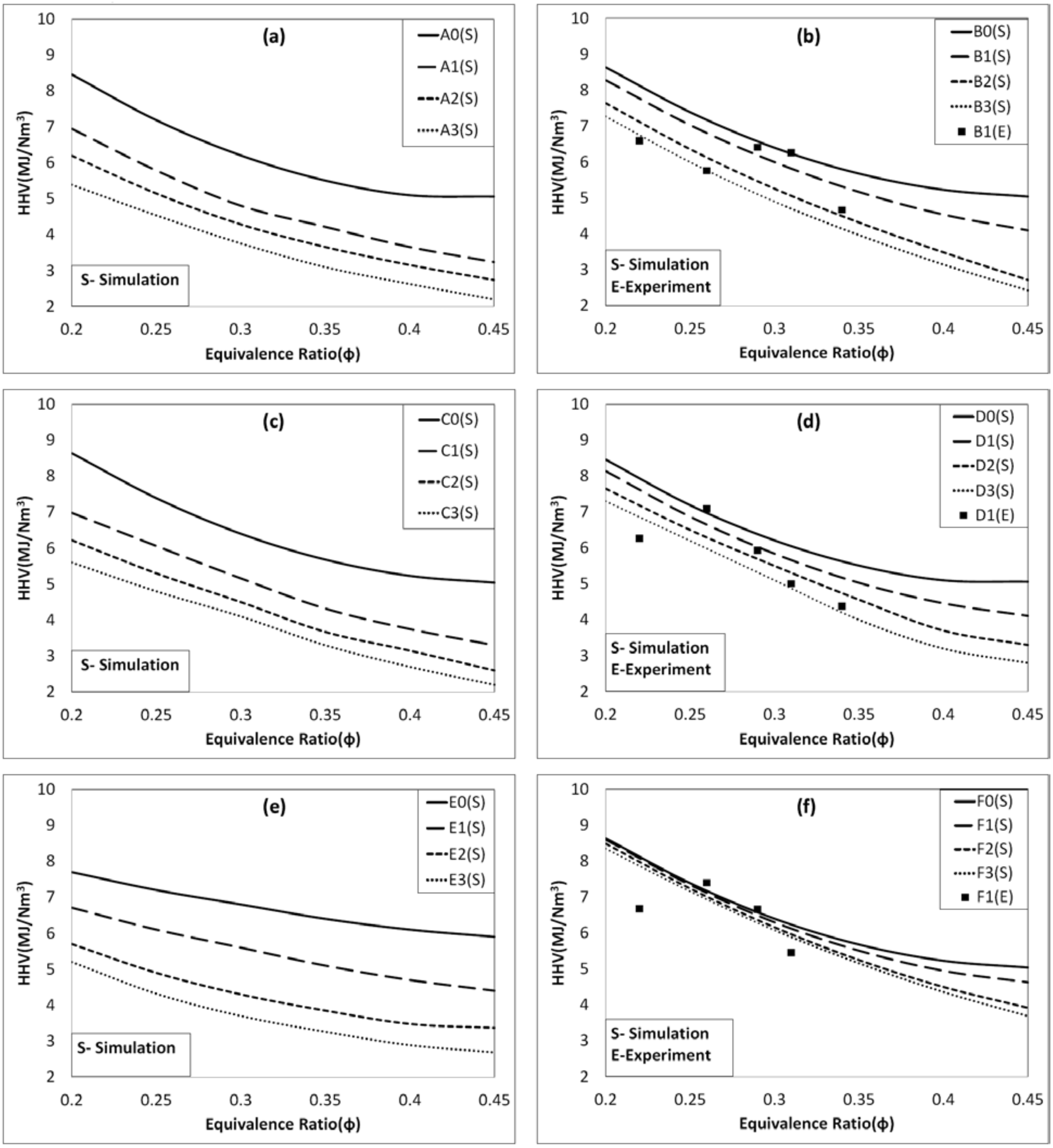

Fig. 6. Variation of HHV with ϕ for the blends, (a) Coconut Shell: Coir Pith. (b) Wood: Rubber Seed Kernel. (c) Wood: Coir Pith. (d) Coconut Shell: Rubber Seed Kernel. (e) Rubber Seed Kernel: Coir Pith. (f) Wood: Coco-nut Shell.

reaches 0.3.The experimental results of the blends, B1,D1, and F1 are also showing the similar trends. Hence it is desirable to use the blends shown in Fig. 5b, Fig. 5d and Fig. 5f.

C. Higher Heating Value

The quality of the producer gas depends on the concentration of combustible gases (*CO*, H_2 and CH_4) and their heating values. A reduction in HHV of gas has been observed with the increase in ϕ (Fig. 6). The gas production rate is almost constant until the equivalence ratio reaches 0.3 (Fig. 5). Therefore a sharp decrease in HHV is observed (Fig. 6b, Fig. 6d and Fig. 6f). Among all the blends, the wood and coconut shell combinations show a stable and high HHV (Fig. 6f). This is due to the superior quality observed in the ultimate analysis (Table 1). It is also observed that the mixing of the feedstock materials reduces the HHV drastically when equivalence ratio is increased from 0.2 to 0.3. Furthermore the increase in equivalence ratio increases N2 dilution in the gas, thus the heating value of the gas reduces. Therefore to maintain a high heating value of the producer gas, equivalence ratio should be kept close to 0.2.

D. Conversion Efficiency

The impact of equivalence ratio on conversion efficiency depicted in Fig. 7 shows that the conversion efficiency is maximum, when the biomass has good HHV and is used alone. Since the conversion efficiency is

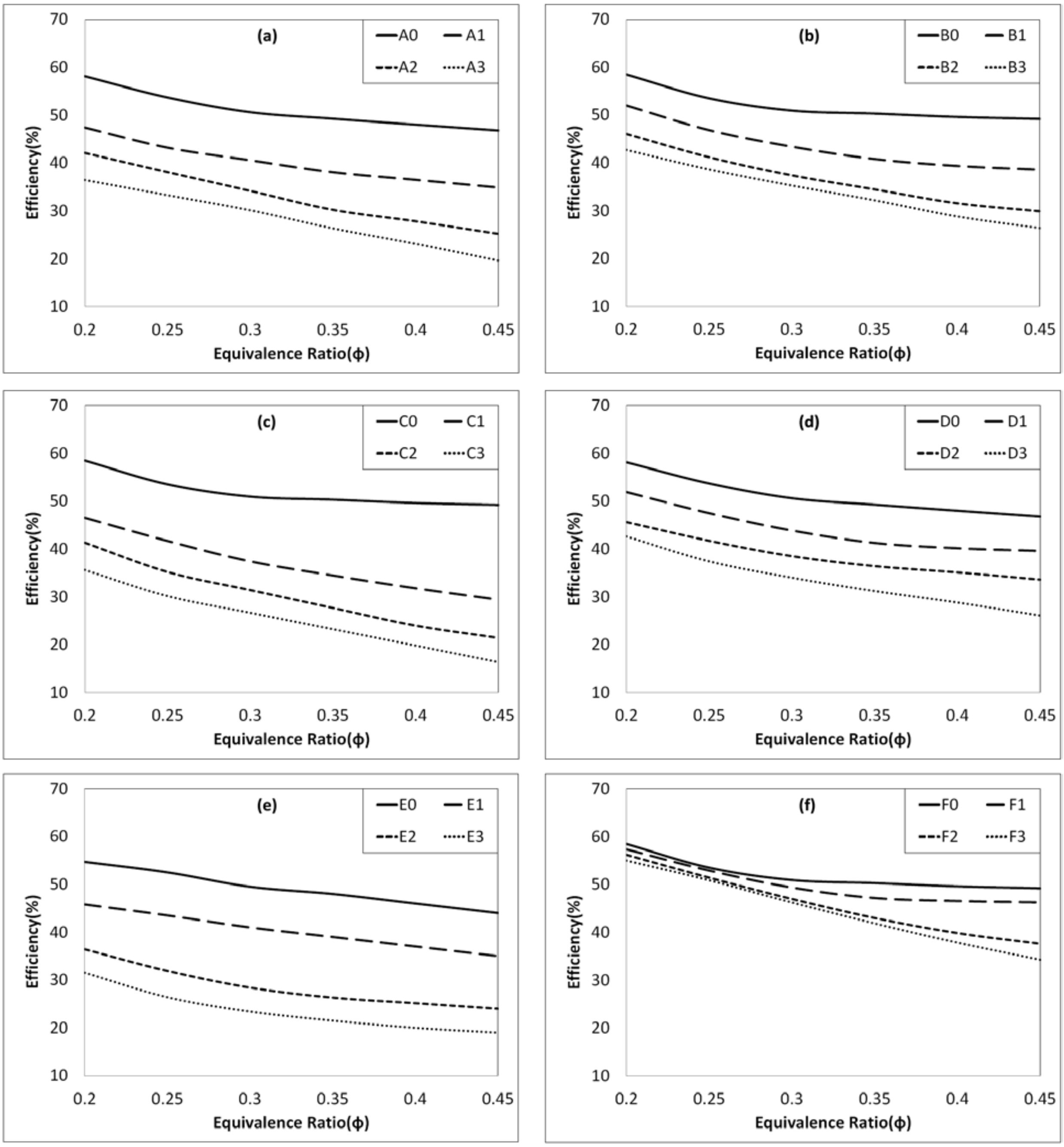

Fig. 7. Variation of Conversion Efficiency with ϕ for the blend, (a) Coconut Shell: Coir Pith. (b) Wood: Rubber Seed Kernel. (c) Wood: Coir Pith. (d) Coconut Shell: Rubber Seed Kernel. (e) Rubber Seed Kernel: Coir Pith. (f) Wood: Coconut Shell.

Table 5. Analytical and Experimental Values of Temperature (K) along the Reduction Zone for the Blends B1, D1 and F1

Blend	ϕ	Study	Reduction Zone Distance(m)				
			0.08	0.16	0.24	0.32	0.4
B1	0.2	T	1362	1340	1318	1296	1274
		E	1388	1336	1294	1278	1254
D1	0.2	T	1285	1275	1264	1254	1244
		E	1267	1252	1271	1264	1132
F1	0.2	T	1170	1160	1149	1139	1130
		E	1145	1138	1141	1124	1116

T-Theoretical, E-Experimental

based on the gas composition and HHV of the producer gas, their experimental values are already discussed in the previous topics, only the simulation results of conversion efficiency is taken for discussion. In all the combinations, a drastic reduction in efficiency is observed when the equivalence ratio is increased from 0.2 to 0.3 and after 0.3 it reduces gradually. This is due to the impact of the gas production rate (Fig. 5). However, the efficiency is maintained at a higher level when both the primary and secondary energy sources have HHV close to each other. In this study, the maximum efficiency is observed for the blend of wood and coconut shell (Fig. 7f).

E. Gas Temperature

The experimental observations and the results from analytical studies on temperature for similar operating parameters have been presented in the Table 5. Since the results from the current simulation and previous studies show the best performance of gasifier at the equivalence ratio of 0.2 (Sheth and Babu, 2009), the same has been considered for this experimental comparison. In both the analytical and experimental studies, a low temperature at the exit of the gasifier has been observed for wood/coconut shell blend with 90:10 composition. This is due to the fact that, all the endothermic reactions have been completed while the gases proceed along the reduction zone.

V. CONCLUSIONS

Experimental and theoretical studies were conducted on a 50kW$_{th}$ downdraft gasifier with biomass blends of various quantities and qualities available in rural areas. The variation of performance parameters with equivalence ratio had been analyzed, and based on the results, the following conclusions are drawn.

1. The deviation of simulation results from the experimental observations is within 10 to 15%. Therefore the proposed model can be used to predict the performance of any biomass blend in a downdraft gasifier.
2. The performances of individual biomasses show that the HHV influence the conversion efficiency of the gasifier. Among the four components, the coir pith shows a poor performance when used with other biomasses. Therefore it can be avoided.
3. All the blends have higher conversion efficiency when the equivalence ratio is close to 0.2. Therefore, irrespective of the composition in blend, to obtain high conversion efficiency, the equivalence ratio should be maintained close to 0.2.
4. The combustible gas composition and conversion efficiency observed from the blends of wood, coconut shell and rubber seed kernels are close to each other. Therefore priority may be given to these materials.
5. The study shows that the binary blends of rubber seed kernel, coconut shell and wood can be used in a commonly available imbert type gasifier to generate producer gas of reasonably good quality.

NOMENCLATURE

A	percentage of ash content in biomass.
A/F	air fuel ratio.
AR	frequency factor.
C	carbon content of biomass in mass percentage.
Cp	molar specific heats (J/molK).
CRF	char reactivity factor.
ER	activation energy.
FC	fixed carbon of biomass in mass percentage.
g	gibbs function of species (J/mol).
hf	enthalpy of formation of species (J/mol).
H	hydrogen content of biomass in mass percentage.
Hf	enthalpy of formation of biomass (J/mol).
K	equilibrium constant of reaction.
KR	equilibrium constant of reduction reactions.
l	number of atoms of hydrogen per number of atom of carbon in the primary energy source.
MC	molecular weight of the combustible part of energy source.
Mw	moisture content in the fuel in mass percentage.
mash	mass flow rate of ash (mol/s).
N	nitrogen content of biomass in mass percentage.
n	number of control volume.
O	oxygen content of biomass in mass percentage.
P	partial pressure of gas species (N/m^2).
p	number of atoms of oxygen per number of atom of carbon in the primary energy source.
Q	heat (J).
Qloss	heat loss (J).
q	number of atoms of nitrogen per number of atom of carbon in the primary energy source.
R	universal gas constant (J/molK).
S	mass percentage of primary energy source.
T	temperature (K).
t	number of atoms of hydrogen per number of atom of carbon in the secondary energy source.
u	number of atoms of oxygen per number of atom of carbon in the secondary energy source.
v	number of atoms of nitrogen per number of atom of carbon in the secondary energy source.
xi	number of moles of species formed.
Y	mole fraction of species.
C	carbon.
CH_4	methane.
CO	carbon monoxide.
CO_2	carbon dioxide.
H_2	hydrogen.
H_2O	water.
N_2	nitrogen.
O_2	oxygen.
ϕ	equivalence ratio.

Subscript

0	reference of temperature.

1 primary energy source.
2 secondary energy source.
a ambient condition.
g gas.
i species.
in inlet condition.
out outlet condition.

Superscript

k kth control volume.

Abbreviation

DAF dry air basis.
HHV higher heating value.

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Received: January 24, 2014. Accepted: November 6, 2014.

Recommended by Subject Editor: Orlando Alfano.