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Experimental and Equilibrium modeling Investigation of rice husk Stratified downdraft gasifier

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Abstract

In this paper, experimental study on transient temperature distribution, assessment of reaction and reduction zone and carbon residue in ash at different equivalent ratio of a stratified downdraft gasifier using rice husk as raw material are investigated. Besides,the equilibrium modeling was employed to predict reaction zone temperature and reaction zone gas composition. Equivalent ratio was varied from 3.90 to 4.50. Our study found that, temperature of combustion and reduction zones were generally higher at a higher air input rate coupled with a faster temperature propagation rate towards upstream of the reactor. Reaction zone temperature prediction using equilibrium model was in good agreement with the experimental result. Maximum cold gas efficiency was obtained at the equivalent ratio 3.90. For all case, considerable carbon residual was indicated by clearly black color in ash.

Keywords:Thermodynamics Equilibrium Model,Stratified Downdraft Gasifier,Rice Husk Fuel.

1. Introduction

Gasification is the thermo-chemical conversion of a solid or liquid feedstock into a valuable and convenient gaseous fuel or chemical product which can be further utilized in various form of thermal energy application. There are many types of conventional gasification reactor available [1]. The main engineering task is to find the method or mathematical model to predict and bare all physics of gasification process. The model will allow engineers to analyze the insight process quality which will enable a more refined idea to further increase gasification efficiency [2]. This paper focuses only on stratified downdraft using rice husks as raw material.

Gasification modeling is divided into two main categories which are 1.) Zero dimension modeling and 2.) CFD modeling. Zero dimension modeling is employed the well-stir reactor concept, with this assumption, the use of simple chemical model to predict species of composition is enabled.CFD modeling accounting on both transport phenomena and fluid dynamics into the model. Therefore, CFD allows more physical insight compare to Zero dimension modeling. More physical parameters are involved in the analysis on the effect of reactor performance and operations. For example, combustion propagation speed, combustion zone thickness, reduction zone thickness etc. CFD modeling can be further divided into 1D modeling and Multi-dimension modeling. In 1D-modeling, fluid dynamic coupling

algorithm can be ignored. The other, the complex physical sub-model,(pyrolysis,combustion,heat conduction) can be integrated into the code without fluid dynamics complication.Therefore, the sensitivity of each sub-model is enabled to point-out.Moreover,It is reasonable to assume 1-D flow in stratified downdraft gasifier since the flow was almost in axial direction along the reactor length. Due to the simplicity but powerful of equilibrium modeling,there are plenty of published papers employed this method to predict fuel type, moisture sensitivity and various operation parameters on gas composition[3][4][5].Some researchers employed CFD model to obtain more physical insight on gasification process [6].In this paper,only equilibrium model is present.

2. Modeling and experimental setup

2.1Gasification Model

The stoichiometric chemical reaction of dry air gasification can be written asEqs.1.

$$CH_xO_yN_z + m(O_2 + 3.76N_2) \longrightarrow x_1H_2 + x_2CO + x_3CO_2 + x_4H_2O + x_5CH_4 + x_6C + (z/2 + 3.76m)N_2 \quad (1)$$

The equivalent ratio from various experimental cases can be converted to obtain *m* value in equilibrium model. Three equations can be derived by the conservation of elemental mass present in the reactants and products.

Carbon balance

$$x_2 + x_3 + x_5 + x_6 - 1 = 0 \quad (2)$$

Hydrogen balance

$$2x_1 + 2x_4 + 4x_5 - x = 0 \quad (3)$$

Oxygen balance

$$x_2 + 2x_3 + x_4 - y - 2m = 0 \quad (4)$$

Three major reaction which are boudauard reaction, *CO* shift reaction and methanation are considered to reach chemical equilibrium in combustion zone. Therefore, additional three equilibrium equations are considered.

Boudouard reaction

$$C + CO_2 \longrightarrow 2CO \quad (5)$$

CO shift reaction

$$CO + H_2O \longrightarrow CO_2 + H_2 \quad (6)$$

Methanation reaction

$$C + 2H_2 \longrightarrow CH_4 \quad (7)$$

The equilibrium constant written in equation (5) (6) and (7) will enable completion of all six equations and to calculate the equilibrium composition of product syn-gas from reaction zone.

Equilibrium constant for boudouard reaction

$$K_1 = \frac{x_2^2}{x_3 x_{total}} \quad (8)$$

Equilibrium constant for CO shift reaction

$$K_3 = \frac{x_5 x_{total}}{x_1^2} \quad (9)$$

Equilibrium constant for methanation reaction

$$K_2 = \frac{x_2 x_1}{x_2 x_4} \quad (10)$$

Where x_{total} is the total number of moles of gas phase species in the product of Eqs.2 While x_6 represent the un-burn solid carbon. Therefore exclude from equation (11)

$$x_{total} = x_1 + x_2 + x_3 + x_4 + x_5 + \left(\frac{z}{2} + 3.76m\right) \quad (11)$$

The value of equilibrium constant is figured out at constant temperature and pressure using the standard state Gibbs function of change. While ΔG_T^0 at particular temperature of each reaction can calculate follow [1]

$$K_i = e^{-\frac{\Delta G_T^0}{RT}}, i = 1,2,3 \quad (12)$$

2.2 Energy equation

In order to calculate temperature of reaction zone the energy balance between reactant and product is used

$$\sum_{i=reactants} x_i h_{f,i}^0 = \sum_{j=products} x_j \left(h_{f,j}^0 + \Delta h_T\right) \quad (13)$$

where x_i is the number of moles of reactants, $h_{f,i}^0$ is the enthalpy of formation of reactants , x_j is the number of moles of product species, $h_{f,j}^0$ is the enthalpy of formation of product species and Δh_T is the sensible enthalpy of product. The above equation can be expressed in the following expanded form when applied corresponding to Eqs.1.

$$\begin{aligned}
&\Delta h_{f,feedstock}^o + m h_{f,o_2}^o + 3.76 m h_{f,N_2}^o \\
&= x_1\left(h_{f,H_2}^o + C_{P,H_2}\Delta T\right) + x_2\left(h_{f,CO}^o + C_{P,CO}\Delta T\right) \\
&+ x_3\left(h_{f,CO_2}^o + C_{P,CO_2}\Delta T\right) \\
&+ x_4\left(h_{f,H_2O(vapor)}^o + C_{P,H_2O(vapor)}\Delta T\right) \\
&+ x_5\left(h_{f,CH_4}^o + C_{P,CH_4}\Delta T\right) \\
&+ x_6\left(h_{f,C}^o + C_{P,C}\Delta T\right) + \left(\frac{Z}{2} + 3.76m\right) \\
&\left(h_{f,N_2}^o + C_{P,N_2}\Delta T\right)
\end{aligned} \quad (14)$$

where C_P is the specific heat at a constant pressure and ΔT is the changes in temperature with respect to reference temperature $(T_1 = 298K)$. The enthalpy of formation for O_2 and N_2 are zero at the reference state therefore the last two terms on left hand side of Equation (14) are eliminated. The enthalpy of formation of feedstock is calculated using the method defined by Syed et al. [1]. In the calculation the presence of nitrogen in the feedstock is neglected as its contribution is small.

2.3 The calculation procedure

Figure.1 the calculation procedure starts by initial guess on the value of Temperature. Then the composition at equilibrium can be calculated by solving the non-linear system of equations by various numerical techniques. After that, obtained compositions are substituted in energy equation to calculate value of gasification temperature. Then,The calculation is repeated until temperature difference between composition calculation and temperature from energy equation are satisfied.

Overall experimental rig set up refer to fig.2 Main reactor made by stainless pipe without fuel feeding and ash remove system.7 thermo couples

was install along axial direction of the reactor to trace on temperature propagation and zone distinction. After fuel was fully feed in the reactor and the Air flow rate was set. Flame could be ignited at the ignition port then the temperature distribution was recorded for every 1 minute intervaluntil the temperature propagation reached to the top portion of the reactor. Equivalent ratio can be calculated by known amount of fuel in the reactor and total air input of each experimental case. This calculated equivalent ratio then will be the model input in accordance with the experimental case. Also temperature propagation speed running to the top portion of the reactor can be calculated.

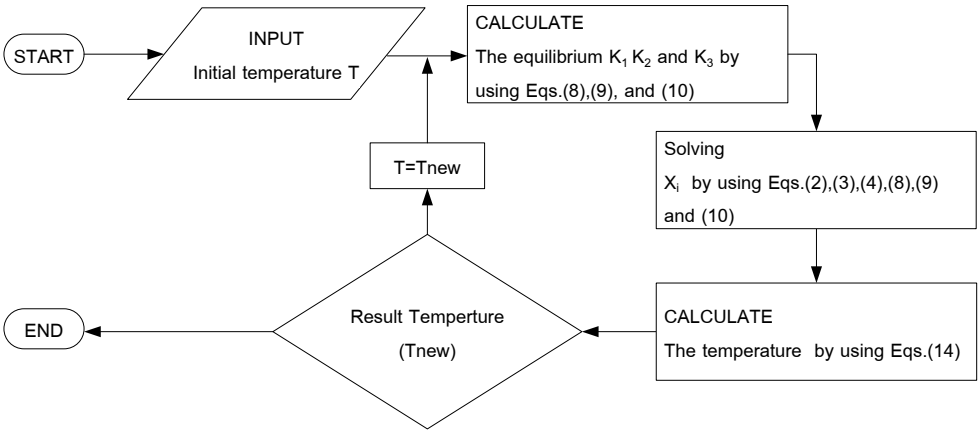

Fig. 1 The calculation procedure.

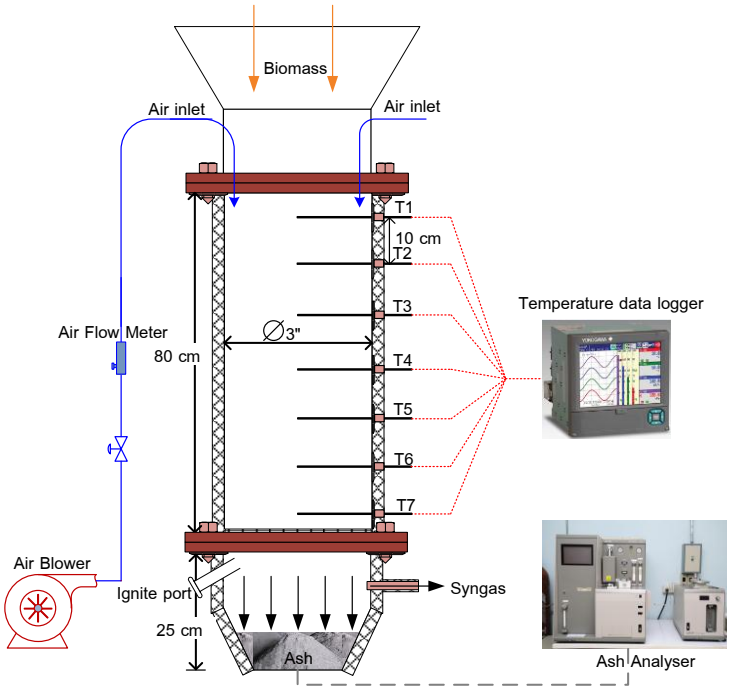

Fig. 2 Overall schematic of experiment apparatus and instrument setup.

3. Result and Discussion

Reaction zone temperature were in good agreement for all cases between experimental and equilibrium model Fig.3 It was shown that as the equivalent ratio increased the reaction zone temperature was decreased. Because less air input allowed less combustion to occur. And resulted in less fuel volatilization due to limited heat release. Note that the reaction zone temperature of experimental cases was indicated by the maximum temperature reading of all thermocouples.

Figure.4 Gas composition prediction from equilibrium model reflected that carbon residual was decreased while CO_2 and CO was increased as the equivalent ratio decreased. The increment of CO_2 and CO were the consequence from more carbon combustion. More air input allowed more heterogeneous of carboncombustion.The H_2O and CH_4 are nearly constant among various equivalent ratio and both of themplayed less important impact on syn-gas composition efficiency.Since they were less amount than CO_2,CO.

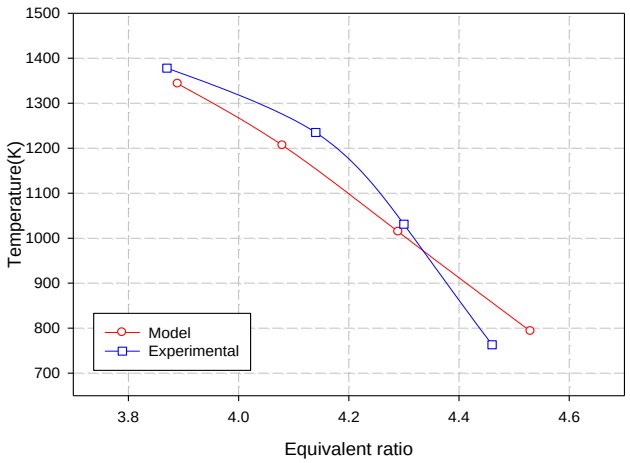

Fig.3 Comparison of the equilibrium analysis and experimental test on temperature.

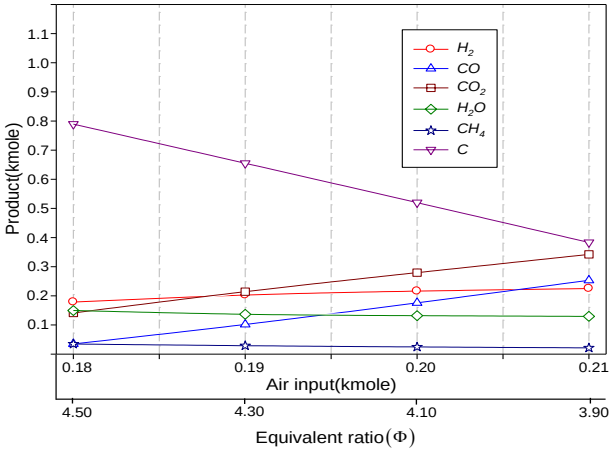

Fig.4 Equilibrium analysis on productgas composition

Regarding to the equilibrium result,CO_2 and CO composition were playing the most important role in syn-gas efficiency.Fig.5 Theywere violently altered with different equivalent ratio. CO_2 and CO were both increased with increased air input. CO_2 was considered as combustion load because it was unable to release heat during the combustion,and unable to consume heat energy via sensible enthalpy heat load, which caused the deterioration in syn-gas heating value. In contrast, CO which considerable released heat during combustion.Increasing in CO species was the main reason for higher CGE value as the input air was increased. CGE value can calculate by eqs.(15)

$$CGE = \frac{HHV_{produc\ gases}}{HHV_{feedstock}} \qquad (15)$$

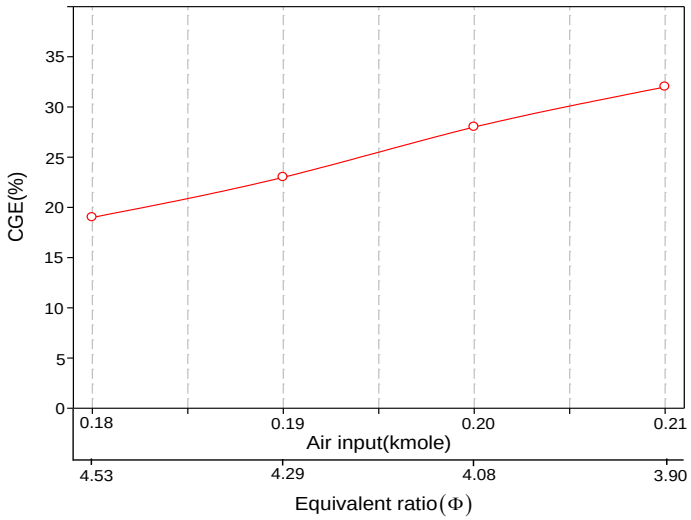

Fig.5 Equilibrium analysis on product CGE.

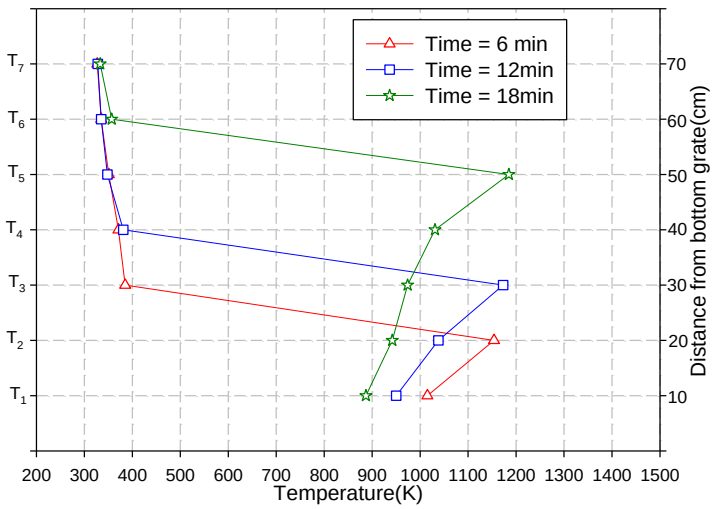

Fig.6 Experimental temperature profiles inside the gasifier($\Phi = 4.10$)

Figure.7 the temperature profile indicated two distinct zones which were 1.) reaction zone where the combustion was taking place 2.) reduction zone was the point where the temperature started to drop, indicated the reduction kinetic which was the process to convert heat into chemical energy. Main processes were various shift reaction, which produced more combustible species and consume combustion load species. CGE of syn-gas was improved in this reduction kinetic.The temperature drop measured at 10 cm after combustion zone is 1030 K at equivalent ratio 3.90, 1016 K at equivalent ratio 4.10, 976 K at equivalent ratio 4.30 and 728 K at equivalent ratio 4.50.The temperature drop indicated that there were not considerably different amount of reduction kinetics for all of the equivalent ratio range. Residual from experimental test showed that there were considerable un-burn carbon for all equivalent ratio see fig.8

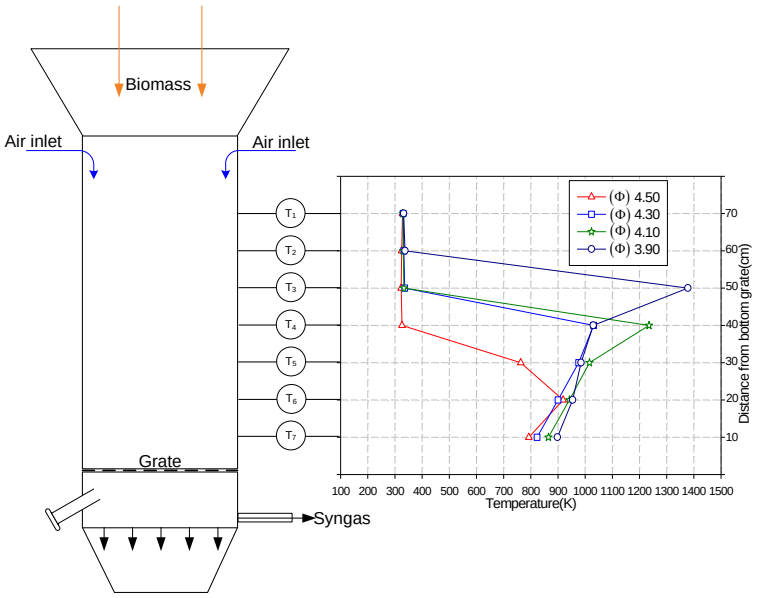

Fig.7 Experimental temperature profiles along axial axis of the gasifier (at time = 15 minute)

(a) Equivalent ratio 3.90 (b)Equivalent ratio 4.10 (c)Equivalent ratio 4.30 (d)Equivalent ratio 4.50

Fig.8 un-burn carbon for all equivalent ratio.

4. Conclusion

Equilibrium modeling was employed to predict reaction zone temperature and reaction zone gas composition . Equivalent ratio was varied from 3.90 to 4.50. It i wasshown that for all of the cases reaction zone and reduction zone were in the order of 10 cm. Maximum temperatures at combustion zone was 1343 K at equivalent ratio 3.90, 1206 K at equivalent ratio 4.10, 1014 K at equivalent ratio 4.30 and 793 K at equivalent

ratio 4.50. The temperature drop measured at 10 cm after combustion zone was 1030 K at equivalent ratio 3.90, 1016 K at equivalent ratio 4.10, 976 K at equivalent ratio 4.30 and 728 K at equivalent ratio 4.50.Temperature of combustion and reduction zones were generally higher at higher air input with faster propagation rate towards upstream of the reactor. Because of lower air input could produce less heat in combustion zone which some of them were expensed in fuel volatilization. Reaction zone temperature prediction from equilibrium model was in good agreement with experimental result. Maximum cold gas efficiency was obtained at the equivalent ratio 3.90.

Since the equilibrium model was address on combustion process, therefore, in this paper, the prediction of temperature, CGE efficiency, gas composition was focused particularly on combustion zone. The following reduction zone which various shift reaction occur will be the future work. Also developing 1D CFD modeling is the main task of ongoing work.

6. References

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