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Experimental and Computational Fluid Dynamics Investigation of Rice Husk Updraft Gasifier with Various Gasification Agents

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Utilising biomass for thermal generation purpose is one of the ways to reduce CO_2 emissions. For that reason, the biomass gasification process is used to produce rich heating value fuel which is known as syngas. Because of the complicated nature of this field, the research should comprise both conducting experimental investigation on actual facilities and developing a numerical model. This study compared the affection of two kinds of gasification agents, the air and the air-steam mixture, on the composition of syngas and cumulative CO. The ratio of steam for the best quality of syngas was then determined. The two-dimensional Computational Fluid Dynamics (CFD) was developed for determining the suitable kinetics model. The parameters of geometry were taken from practical pilot plant gasifier. The validation process for this simulation was carried out by comparing the simulation data with experimental data which was measured by online gas analyser-TESTO 350XL. The results illustrate the influence of air-steam mixture on the composition of CO and H_2 in syngas, H_2/CO ratio, and the advantage of using the stream in gasification on both experimental and simulation results.

1. Introduction

Rice husk is becoming a popular fuel use for thermal purpose in Vietnam as the country has huge rice husk sources. It can meet 27 % of demand for energy consumption by using this biomass energy resource (Tu et al., 2010). The gasification of rice husk was not well-known in the existing literature. This technology is considered as sophisticated processes such as drying, pyrolysis, solid and gas combustion were taking place simultaneously. The formation of tar in gasification process and the low quality of product syngas is the major drawback of this technology. To overcome these disadvantages, this research focuses on investigating various gasification agents. Modelling investigation was also conducted to better understand the mass transfer, heat transfer, species transport, and chemical reaction phenomenon in the process. Four groups of modelling methods were carried out: thermodynamic equilibrium, kinetic, computational fluid dynamics (CFD), and artificial neural network (Basu, 2010). In 2014, the research of Ismail and El-Salam (2014) showed the 2D mathematical model for fixed bed updraft gasification.

In 2017, the research group of Muslim et al. (2017) had published the study of “Effects of Purification on the Hydrogen Production in Biomass Gasification Process”. In this study, the fluidised bed reactor produced approximately 7.95 % amount of hydrogen gas whilst it was only 6.75 % hydrogen gas for fixed bed reactor (Muslim et al., 2017). In another approach, Khezri and Karim Ghani (2017) had carried out the computational works in fluidised bed reactor in the paper of “Process Computational Modelling of Gas-Solid Hydrodynamics and Thermal Conduction in Gasification of Biomass in Fluidised Bed Reactor”. The computational result showed the solid volume fraction at air velocity from 0.07 m/s to 0.3 m/s. The air velocity at 0.2 m/s, the bed expansion was maximum and the solid particles were fluidising in the gasification region (Khezri and Karim Ghani, 2017).

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The aim of this paper this paper is to combine experiment and modelling method for optimising design parameters of updraft fixed bed gasifier to obtain the high quality syngas. The experiment was carried out in the practical pilot gasifier with batch feed model, and the two-phase model was developed by using the Euler-Euler approach. This time-dependent model consisted of several sub-models including reaction models, the porous zone model for simulating packed bed, and the radioactive model in the solid phase. The rice husk bed was initially ignited by patching the high-temperature zone and then this model operated by the heat emitted by combustion reactions until the material is depleted. The CFD tool ANSYS Fluent 14.5 was used in this study to convert mathematical model and 2D practical gasifier geometry into the numerical model for simulating gasification process. The resulting data of the CFD model was validated with experimental result from the pilot gasifier. The kinetic data of gas-phase reaction are shown in Table 1.

2. Mathematical model

Continuity equations in gas phase and solid phase are shown in Eq(1) and Eq(2) as follows:

$$\frac{\partial(\alpha_g\rho_g)}{\partial t} + \nabla.\left(\alpha_g\rho_g v_g\right) = m_{gs} \tag{1}$$

$$\frac{\partial(\alpha_s\rho_s)}{\partial t} + \nabla.\left(\alpha_s\rho_s v_s\right) = m_{ss} \tag{2}$$

Where α is void fraction in bed, ρ is density in gas and solid phase, kg/m^3, v is velocity, m/s, and m is source term of mass balance equation.
Momentum equations in gas phase and solid phase are shown in Eq(3) and Eq(4) as follows:

$$\frac{\partial\left(\alpha_g\rho_g v_g\right)}{\partial t} + \nabla\left(\alpha_g\rho_g v_g v_g\right) = -\alpha_g\nabla p + \nabla\left(\tau_g + \tau_g^t\right) + \alpha_g\rho_g g + m_{gs}v_s + \beta(v_g - v_s) \tag{3}$$

$$\frac{\partial(\alpha_s\rho_s v_s)}{\partial t} + \nabla\left(\alpha_s\rho_s v_g v_s\right) = -\alpha_s\nabla p - \nabla p_s + \nabla(\tau_s + \tau_s^t) + \alpha_s\rho_s g + m_{ss}v_s + \beta\left(v_g - v_s\right) \tag{4}$$

Where p is pressure, Pa, τ is shear stress, Pa, v is velocity, m/s, and β is coefficient of velocity.
Energy equations in gas phase and solid phase are shown in Eq(5) and Eq(6) as follows:

$$\frac{\partial(\alpha_g\rho_g E_g)}{\partial t} + \nabla g\left(\alpha_g\rho_g v_g E_g\right) = \nabla g k_{eff,g}\nabla T_g + S_g \tag{5}$$

$$\frac{\partial(\alpha_s\rho_s E_s)}{\partial t} + \nabla g(\alpha_s\rho_s v_s E_s) = \nabla g k_{eff,s}\nabla T_s + S_s \tag{6}$$

Where E is enthalpy, Pa, k is thermal conductivity, W/m.K, T is temperature, K, and S is source term of energy balance equation.
Species transport equations are described as follows:

$$\frac{\partial(\rho_g\alpha_g Y_{i,g})}{\partial t} + \nabla\left(\rho_g\alpha_g v_g Y_{i,g}\right) = \nabla g\alpha_g J_{i,g} + \alpha_g R_{i,g} \tag{7}$$

$$J_{i,g} = -\left(\rho_g D_{i,g} + \frac{\mu^t}{Sc_t}\right)\nabla Y_{i,g} - D_{T,i}\frac{\nabla T}{T} \tag{8}$$

Where ε is dissipation rate of turbulent kinetic energy, m^{-2} s^{-3}, Y is mass fraction of volatile matter, D is mass diffusion coefficient of gas, m^2/s, μ is dynamic viscosity, Pa.s, Sc is Schmidt number, and R is reaction rate.
Chemical reactions model are showed as below:

$$H_2O\ (l) \rightarrow H_2O\ (g) \tag{R1}$$

$$CH_hO_o \rightarrow n_{p,C}C + n_{p,CO_2}CO_2 + n_{p,CO}CO + n_{p,CH_4}CH_4 + n_{p,H_2}H_2 + n_{p,C_2H_2}C_2H_2 + n_{p,H_2O}H_2O \tag{R2}$$

$$C + \left(\frac{1-a}{2}\right)O_2 \rightarrow aCO + (1 - a)CO_2 \tag{R3}$$

Where n and a are the stoichiometric coefficients
The kinetic data of gas-phase reaction are shown in Table 1.

Table 1: Kinetic data of gas-phase reaction

Reaction	A ($kmol.m^3/s$)	E (J/kmol)
$CO + H_2O \leftrightarrow CO_2 + H_2$	1,389	1.256 x 10^7
$CO + \frac{1}{2}O_2 \rightarrow CO_2$	1.7 x 10^8	2.239 x 10^{12}
$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$	3.1 x 10^7	9.87 x 10^8
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	2.027 x 10^8	2.119 x 10^{11}
$C_2H_2 + \frac{5}{2}O_2 \rightarrow 2CO_2 + H_2O$	1.25 x 10^8	3.655 x 10^{10}

3. Experiment and Modelling Setup

3.1 Experiment setup

The pilot gasifier as shown in Figure 1 was used as a domain of the CFD model.

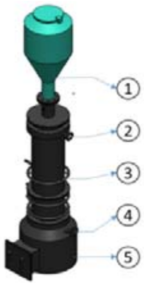

Figure *1: Fixed-bed updraft gasifier*

Rice husk was fed at the top of the gasifier (3) via the feeder (1), and then it was ignited by heat from LPG flame which was removed after a certain amount of time. It was pyrolysed to release CO, CO_2, H_2O, CH_4 and tar from char. After the release of volatile matters, the char was burned and gasified with CO_2 and H_2O. It was the main reaction to produce H_2 and CO. The experiment was conducted in 1 h for the 1 kg packet of rice husk. The air at room temperature and the saturated steam were supplied from the bottom though inlet pipe (1). In the end of the experiment, rice husk ash was collected in ash chamber (5).

In this experimental facility, the temperature along the centre line of gasifier was measured in 4 places with the distance from grate of 100 mm, 220 mm, 340 mm, 655 mm. The Testo 350XL was used as a gas analyser which was able to display the percentage of CO, CO_2, O_2 and H_2.

3.2 Boundary and Initial condition

The gasification process occurred in a reactor. It is assumed that the reactor uses air at the room temperature and saturated steam as gasification agent. Those streamlines were supplied at a constant velocity from the bottom. The ignition process of this model was simulated by patching a temperature as the initial condition similar to the magnitude of flame temperature at the position of 340 mm above the grate.

The initial pressure was taken as the atmospheric pressure within the reactor. The solid phase was a patch in the whole computational domain with mass fraction similar to the proximate analysis of rice husk as the initial temperature was 300 K. At the inlet boundary condition, velocity magnitude, temperature and the molar fraction of substances O_2, N_2, H_2O in each case study were indicated in Table 2. Pressure outlet configuration was chosen for the outlet boundary condition. Insulated wall was set for wall boundary condition.

Table 2: Operation conditions for running simulation

Case	Temperature (K)	Velocity (m/s)	S/A (vol/vol)	Mole fraction of O_2 (mol/mol)	Mole fractionof N_2 (mol/mol)	Mole fraction of H_2O (mol/mol)
1	300	0.165	0	0.21	0.79	0
2	318.6	0.21	0.25	0.17	0.63	0.2
3	331	0.25	0.5	0.14	0.53	0.33
4	340	0.29	0.75	0.12	0.45	0.43

4. Results and discussion

The temperature and composition profiles obtained from case 1 experiment are presented in Figure 2a and 2b. The peak value of gas composition and temperature for each case were taken from the graph to compare the efficiency of the batch process among all cases. The peak gas composition and value of CO/CO_2, and H_2/CO obtained from each air steam ratio are displayed in Figure 3a and 3b.

In Figure 3a, H_2 composition increased dramatically when the value of air steam ratio was increased. The H_2 content of the synthesis gas increased significantly with respect to the steam-air ratio until it reached its maximum value and then decreased slightly. Ismail and El-Salam (2014) also achieved the same result with the pine wood chips. The influence of the mass ratio of steam to air agents, S/A, on H_2 content can be explained as follows:

When increasing the amount of the steam entering the system, the composition increased as a result of the water-gas shift, $CO + H_2O \leftrightarrow CO_2 + H_2$ occurred with the equilibrium balance to the right. The H_2/CO ratio also increased with the S/A ratio and decreased when the maximum value had been reached for the same reason.

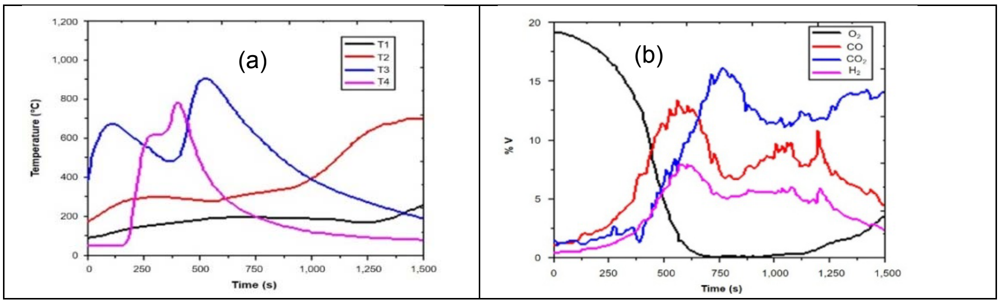

Figure 2: (a) Temperature change and (b) gas change over time with air agent

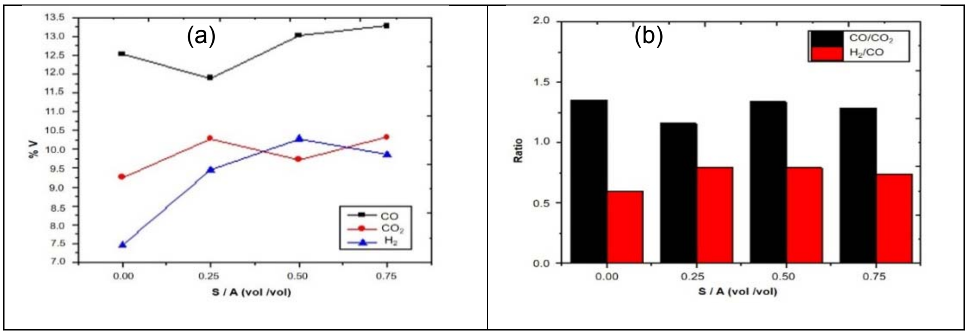

Figure 3: Comparison of (a) peak gas composition and (b) several gasratios from experiment

The important reaction in gasification is the reaction of coal gasification with steam, $C + H_2O \rightarrow H_2 + CO$. According to the author Basu (2010), the dynamics of this reaction were of the form and as a result, the increase in the proportion of water vapor also increased the composition of H_2 in the synthesis gas. As more steam was supplied, the pressure loss due to fluid flowing through the material areas and the pipeline effect, and the structure of the device making steam condensed that affected the combustion process, influenced the heat generated by the fire reaction while simultaneously making the gasification process to recover heat. The temperature varied from 850 °C to 1,050 °C as the rate of steam increased from 0 to 0.75. The highest temperature was taken place in the fire zone with the rate of steam exceeding 0.5.

The influence of S/A ratio i to CO is shown in Figure 5a, the CO content decreased as the S/A ratio increased from 0 to 0.25 and then increased slowly when the S/A ratio were 0.5 and 0.75. This can be explained as follows:

The water-gas shift reaction, $CO + H_2O \leftrightarrow CO_2 + H_2$, moves to the right when the rising steam decreases the CO content of the gas mixture. It is an exothermic reaction, so when the ambient temperature rises, the reaction moves to the left, producing more CO. The opposite effect makes the content of CO not linear. It was necessary to clarify the effect of each effect by extending the scope of the experiment. Non-linearity also occurred with the composition of CO_2 in the synthesis gas. In general, the content of CO_2 in the experiment measured was between 9 – 10 %, which is not much different from the 10 – 12 % achieved by Muhammad

Jalil Arif with Continuous Updraft Gasifier (Arif, 2013). The model was validated by comparing the simulated results with the data obtained from the experimental gasifier. The results of CO, H_2 content in the simulation were compared with experimental data at different S/A ratios. Figure 4a and 4b show the highest CO and H_2 content obtain with different S/A ratio and simulations.

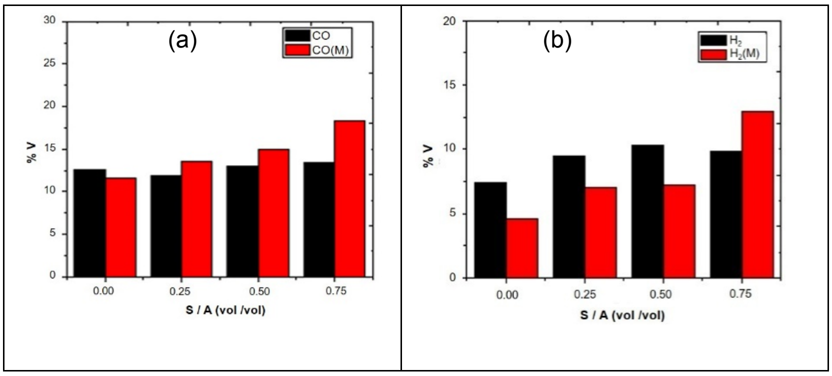

Figure 4: (a) CO and (b) H_2content in experimental and simulation operating conditions

Evaluating the impact of the steam ratio on some of the parameters of the process showed that the simulation results were similar to the experimental conditions of the operating conditions of 0, 0.25, 0.5. Under operating conditions of 0.75, the simulations differed significantly from the experimental ones. The H_2 content was more deviated between simulation and reality than CO. Figures 5 to 7 show the distribution of gasification velocity, char gasification and reaction water gas shift responded in simulated cases.

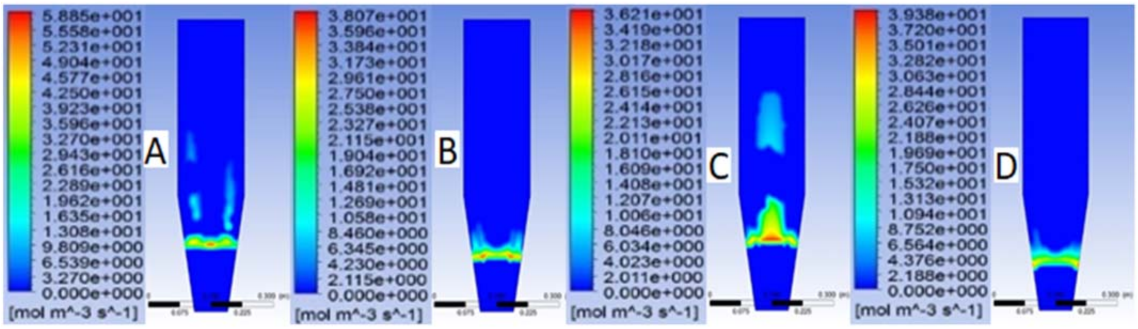

Figure 5: Distribution of char gasification velocity with operating conditions (A): S/A = 0; (B): S/A = 0.25; (C): S/A = 0.5; (D): S/A = 0.75

Figure 5 showed that the velocity in case of air used as gasification agent was highest. The mixture of air and steam showed the gasification velocity lower.

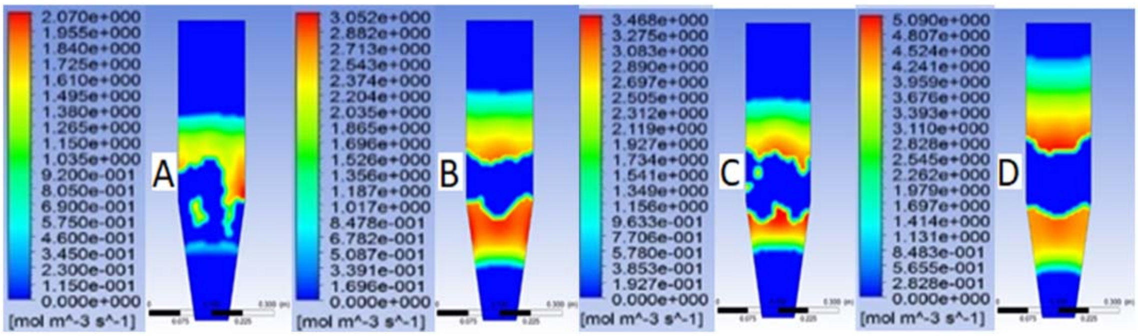

Figure 6: Distribution of char gasification reaction rate velocity with operating conditions (A): S/A = 0; (B): S/A = 0.25; (C): S/A = 0.5; (D): S/A = 0.75

In Figure 6, the reaction rate of char gasification in the case of more steam had taken place intensively. The computational results showed the reaction was occurring in the whole domain of simulation. The reaction with steam happened almost instantly as the gasification agent was injected into the equipment.

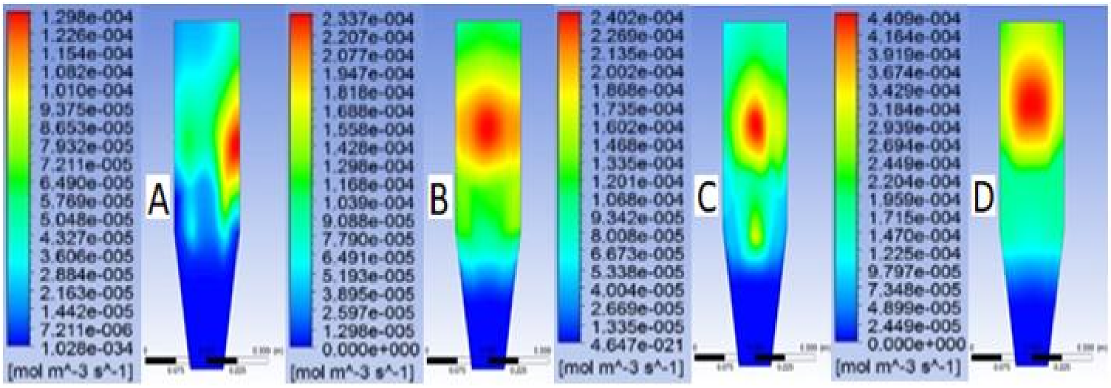

Figure 7: Distribution of water gas shift reaction rate with operating conditions (A): S/A = 0; (B): S/A = 0.25; (C): S/A = 0.5; (D): S/A = 0.75

Similarly, in the computational results, the water gas shift reaction rate had taken place severely in the case where the steam and air ratio were 0.75. The simulation result in the case of air only was the lowest as the reaction occurred partially in the computing domain.

5. Conclusions

The multiphysics modelling of rice husk gasification was investigated in this paper. In the calculation, the dynamic model with a Euler-Euler approach combining with UDFs code was applied. The entire model of heat transfer equations, mass transfer equations, and momentum equations in the porous zone were included in the packed bed model. The computational results were fitted to the experimental results and showed good agreement with the general theory of the packed bed combustion.

In the computational work, the temperature was from 400 °C to 900 °C in the two different areas in the chamber. The highest CO content in fluent modelling was about 2,200 mg/m^3. The S/A ratio of 0.5 appeared to be the optimum condition with respect to the quality of gas. The concentration of CH_4 was very difficult to sample in the experiment, but this model could be used to predict the composition of produced gas.

The model can be further used to perform parameter studies in the geometry of gasifier to find the optimum quality of synthesis gas.

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