Experimental and Numerical Studies of Combustion Characteristics in Swirling Fluidized Bed Gasifier Using Palm Cake as Feedstock

Wasu Suksuwan¹, Mohd Faizal Mohideen Batcha², Arkom Palamanit³ and Makatar Wae-hayee*¹

¹Department of Mechanical Engineering, Faculty of Engineering, Prince of Songkla University, Hatyai, Songkhla 90112, Thailand
²Center for Energy and Industrial Environment Studies, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, Malaysia
³Energy Technology Program, Department of Specialized Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand.

*E-mail: wmakatar@eng.psu.ac.th

Abstract. In this work, combustion characteristics in swirling fluidized bed gasifier using palm cake as feedstock was studied experimentally and numerically. A 3-D numerical model of reactor was created using ANSYS (Fluent) and was compared with experiment in the same scale. The diameter (D) was 0.20 m, and the reactor length was 1.50 m. The double air inlet pipe with an inner diameter of 46.8 mm was assembled tangentially to the bottom of the reactor. An equivalent ratio (ER) was fixed at ER=0.3. The results showed that the result of experiment and numerical studies is almost similar. For highest temperature of the reactor occurred in combustion zone which is high from reference point (bottom end of the reactor) of 0.25 m for experiment and 0.35 m for simulation. For swirling flow pattern was occurred at the bottom rather than the top of the reactor. So, the result of numerical studies can predict the phenomena inside the reactor which is similar to experiment test.

1. Introduction

Gasification [1] is a chemical process that convert carbonaceous materials like biomass into useful convenient gaseous fuel, which include composition gas such as carbon monoxide, hydrogen, methane, carbon dioxide, oxygen, nitrogen, and C2H₅ using incomplete combustion. The gasification process can be divided to four steps i.e. (1) drying, (2) pyrolysis or devolatilization, (3) combustion or oxidation, and (4) gasification or reduction. For types of gasifier reactors consists of (1) fixed bed gasifier which includes up-draft, down-draft and cross-draft, (2) fluidized bed gasifier which includes circulating fluidized bed, and bubbling fluidized bed, and (3) entrained flow gasifier. For selecting, it depends on types of biomass or materials, technology, heat load, required product, environment, and economy [2, 3].

The fixed bed gasifier is commonly used in households, boiler, drying, and small industries [4] which used in heating applications for food or manufacturing processes. This type of reactor is relatively small, simple to design and easy to maintain, but has some limitations in using non-uniform fuel size and variation thermal loads. For medium and large industries such as biomass power plants, waste
incineration plant, cement manufacturing plants etc. fluidized bed gasifier were often used [5], because this type of reactor can combust fine solid fuels having non-uniform size and has the flexibility to accommodate wide range of solids or mixed solids. However, the design is more complex equipment and requires higher investment costs than a fixed bed gasifier [6].

In this study, gasification of oil palm cake, one of the biomass available in abundance in Thailand was studied experimentally and numerically by using the commercial computational CFD package, ANSYS-Fluent. The gasification took place in a swirling fluidized bed gasifier with two air inlets at the bottom of the reactor, based on our initial cold flow studies. The cold flow studies found that double air inlet connected tangentially at the bottom of the reactor provides better swirling motion in the bed [7, 8] and hence advantageous for gasification. The equivalence ratio, ER for gasification was fixed at 0.3 in which only 30% of air required from stoichiometric combustion was supplied, similar to previous studies by [9, 10].

2. Experimental model

The schematic diagram of the swirling fluidized bed gasifier is shown in Figure 1. The diameter of reactor (D) is 0.20 m and the total height from the bottom to the top (H) is 1.50 m. The double air inlet at the bottom of the reactor which creates swirling in the bed has a diameter (d) of 46.8 mm each.

![Schematic diagram of swirling fluidized bed gasifier](image)

Figure 1. Schematic diagram of swirling fluidized bed gasifier

A small quantity of gasoline was used as igniter fuel to initiate the combustion process in the reactor. This was immediately followed the gasification process where the reaction produces composition gas, tar, volatiles, and ash. The product from gasification flows to the cyclone where the composition gas was separated from tar and ash which re-enters the reactor. The composition gas sample was collected at 15 minutes intervals. The gas sample was sucked by a ring blower where they were cooled and cleaned by five step water scrubber for analysis.

The palm kernel cake was using as feedstock which was less than 10 mm. For parameter condition of equivalent ratio (ER) was calculated from ultimate analysis and proximate analysis of palm kernel
cake as shown in table 1. They were evaluated using CHNS/0-2000 and MACEO TGA respectively, available at the Scientific Equipment Center, Prince of Songkhla University.

| Parameter                     | Unit       | Evaluated                | Value |
|-------------------------------|------------|--------------------------|-------|
| Ultimate analysis             |            |                          |       |
| Carbon (As received basic)    | % wt.      | CHNS/0 Analyzer          | 47.01 |
| Hydrogen (As received basic)  | % wt.      | CHNS/0 Analyzer          | 6.20  |
| Nitrogen (As received basic)  | % wt.      | CHNS/0 Analyzer          | 1.17  |
| Oxygen (As received basic)    | % wt.      | CHNS/0 Analyzer          | 39.18 |
| Sulfur (As dried basic)       | % wt.      | CHNS/0 Analyzer          | 0.16  |
| Proximate analysis            |            |                          |       |
| Moisture content (As received basic) | % wt. | ASTM D7582 | 6.12 |
| Fixed carbon (As received basic) | % wt. | ASTM D7582 | 17.67 |
| Volatile matter (As received basic) | % wt. | ASTM D7582 | 70.61 |
| Ash (As received basic)       | % wt.      | ASTM D7582               | 5.60  |

Fuel was fed at a constant rate of 3 kg/hr and the air velocity at each inlet was measured at 0.123 m/s (for each inlet), corresponding to an equivalence ratio of 0.3. The temperature at the reactor core was measured using thermocouples type S and K as shown in Figure 1. Type S thermocouples was positioned at the bottom part of the reactor (T.1 and T.2) due to the higher temperatures at this location followed by type K thermocouples at the upper part of the reactor and designated as T.3, T.4, T.5 and T.6. To reduce heat loss, the reactor was insulated using high temperature insulator (KAOWOOL, ASK-7912-H 8P Blanket 1,400°C). The temperatures were measured every minute throughout the experimental work.

The carbon monoxide content in the composition gas was measured using flue gas analyser (Testo 300). The composition gas sample was collected at an interval of 15 minutes as described earlier.

3. Numerical simulation model

3.1. Computational model and boundary conditions

The swirling fluidized bed gasifier was model ANSYS-Fluent where a 3-D numerical domain was created as shown in Figure 2. The domain matches the dimensions of the actual reactor. The details of boundary conditions were summarized in Table 2. The boundary conditions were divided into 4, while the double air inlets were assembled tangentially to the diverging part of the reactor, about 0.15 m from the bottom end. The fuel inlet was located at the bottom end of reactor. The air outlet was located at the top of the reactor. The surface of the reactor was defined as wall in this domain while the experimental parameters were as in Table 2. the effect of equivalent ratio on syngas properties on the same mass flow rate 3 kg/hrs of fuel inlet and 0.123 m/s of velocity inlet is compared.

| Boundary condition | Define                           |
|--------------------|----------------------------------|
| Air inlet          | Velocity inlet (0.123 m/s)       |
| Air outlet          | Pressure outlet (1 atm)           |
| Fuel inlet          | Fuel inlet (3 kg/hrs)            |
| Surfaces of reactor | Wall                             |
3.2 Grid generation and grid dependency

Figure 3 shows grid generated the rom numerical model of the swirling fluidized bed gasifier which was mostly designed as a rectangular grid. The generated grids were refined at several locations. The finest mesh was generated at conical part of the reactor (the bottom of reactor) due to the higher velocity at this location. As for middle part of the reactor, the generated grid was the largest while the top and bottom part of the reactor has relatively finer meshing. It was calculated that total number of generated grids was 1.93 million elements, similar to our previous work [7] in which the details of grid dependency test was reported.

3.3 Calculation method and algorithm

Computations were conducted by solving Reynolds averaged continuity and Navier-Stokes equations under existing boundary conditions. K-epsilon model which was the viscous model has been adopted.
here as it was known to excellently predict the solutions of internal flow with moderate computation cost. The radiation model used in this work is Discrete Ordinate (DO) model. For species, the species transport model from the proximate analysis and ultimate analysis of palm cake were defined in this model.

The SIMPLE algorithm used associated upwind scheme which were separated to 2 upwind schemes. The first order upwind scheme used for turbulent kinetic energy and turbulent dissipation rate and discrete ordinates. The second order upwind scheme using for pressure, momentum, volatiles, CO$_2$, H$_2$O, CO, and energy. The convergence of iterative solution was met when the residual of all the variables were less than $1 \times 10^{-4}$ for all residuals.

4. Result and discussion

4.1. Temperatures profile along the reactor

The result of temperature profiles along the swirling fluidized bed reactor for both experimental and numerical studies for equivalence ratio of 0.3 were shown in Figure 4. The temperature profiles during experiment were measured at 6 positions (T.1 – T.6) corresponding to H = 0.25, 0.55, 0.65, 0.95, 1.10, and 1.25 m, respectively. As for the temperature profile from numerical study, the H ranged 0 - 1.4 m which they were captured every 0.1 m. The result shown that the temperatures at T.1, T.2 and T.3 from experiment were similar to the numerical studies while the temperatures T.4, T.5, T.6 were found to be slightly higher.

The outlook of the highest temperature inside the reactor of experimental and numerical studies is occurred at combustion zone with a reference point of H = 0.25 m for experiment and 0.30 m for numerical studies which shows that the numerical results can predict the temperatures well.
The temperature contour from the numerical studies was also shown in Figure 4. The combustion zone occurred at the bottom side of the reactor. The fuel was rotated in a swirling pattern around the reactor by air due to their tangential entry into the bed. This is the location where the oxygen from the air first reacts with the fuel. The temperature profile at the reactor core provides characteristic of the flame which was separated into 2 layers, resembling the flame pattern of a non-premixed combustion.

4.2. Numerical Studies of contour profiles of the reactor

Figure 5 presents the velocity contour at the bottom of the swirling fluidized bed reactor at height of 0 to 0.45 m from the bottom. The air was fed at $H = 0.15$ m. The flow took place to the center before returning to the reactor side at $H = 0.25$ m. But due to the lower air velocity, the flow was not symmetrical in both sides. The u-component of velocity (X-axis) in the reactor at different levels along the reactor height were shown in the Figure 5 (a) – 5 (d). At the level of air inlet ($H = 0.15$ m) as shown in Figure 5 (a), the velocity profiles are symmetry in X-axis. The position of the highest velocity occurred at the range of 2 to 4 at the right side and followed by -4 to -2 of the left side. At the reactor height of $H = 0.25$ m (Figure 5 (b)), the magnitude of velocity separated from the center which has the same maximum velocity on both sides at -4 and 3. The u-component velocity on X-axis of this position is symmetry than at $H = 0.15$ m and $H = 0.35$ m. For $H = 0.35$ m (Figure 5 (c)), the u-component velocity was asymmetry because this position is matching the position of the maximum temperature of the reaction which is shown in figure 4. The highest velocity is included at the right side (4 to 6 cm). Figure 5 (d) shows the u-component velocity at $H = 0.45$ m which is return to symmetry at both sides. The magnitude velocity is lower than previously position which is shown that the velocity above of this position isn't focussed.

![Figure 5. The velocity contours and u-component velocity of numerical studies](image-url)
Figure 6 shows the contours profiles of carbon monoxide and volatiles which are important for gasification process on fluidized bed. For the volatiles mass fraction is including methane (CH₄), Hydrogen (H₂), and light hydrocarbon gases (C₂Hₙ). The starting zone for production process were generated at the bottom of the reactor. It is a combination of the combustion zone, pyrolysis zone and the reduction zone. Considering, the carbon monoxide and volatiles which are shown in figure 6 is maximum occurred in the middle of H = 0.15 m to H = 0.25 m of reactor. For carbon monoxide at above H = 0.25 m is a little generated which is higher than H = 0.35 m isn't changed. For volatiles is demonstrated at H = 0.25 m to H = 0.45 m, while no change was seen beyond this height.

4.3. Composition of syngas.
The composition gas at gas outlet was compared with Nuno et. al [11] as shown in Figure 7. They reported the experiment result of varied ER on syngas molar fraction by using the pilot thermal plant is based on bubbling fluidized bed technology and using municipal solid waste as feedstock. It was found that the numerical results were close to those by Nuno et. al where the important component of syngas were carbon monoxide and volatiles. The volatiles mass fraction of numerical studies was slightly higher than experimental (about 2%). The carbon monoxide fraction from numerical study showed a difference about 11% compared to the experimental result. This may be due to the different type of biomass was used as feedstock.
Figure 7. Comparison between composition of syngas.

5. Conclusion
A swirling fluidized bed gasifier using palm cake as feedstock was successfully studied experimentally and numerically. The comparison of temperatures between these two studies indicated small difference, hence proving a reliable numerical prediction was achieved. This was also confirmed by the velocity contour inside the reactor, particularly at the bottom of the reactor such as H = 0.15 m, H = 0.25 m, and H = 0.45 m where swirling flow was induced. The contour of syngas of from gasification process were also obtained at the bottom of the reactor where there was a combination of combustion zone, pyrolysis zone and the reduction zone. Meanwhile, the composition gas at gas outlet is similar to the result of Nuno et. al [7]. It can be concluded that the numerical studies were successful and can safely be used for scaling up purposes of the reactor or predicting different experimental conditions by varying the equivalence ratio as well as fuel feed rate.

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