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Experimental and Numerical Study of Adding Bed Material in Swirling Gasification Using Palm Cake as Feedstock

Satawat Khakkharo[1,2], Muhammad Arsal Cheema[1,2], Wasu Suksuwan[3], Arkom Palamanit[2], Mohd Faizal Mohideen Batcha[4], Makatar Wae-hayee[1,2]*

[1] *Department of Mechanical and Mechatronics Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90112, THAILAND*
[2] *Biomass Energy and Sustainable Technology (BEST) Research Center, Energy Technology Program, Department of Interdisciplinary Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90110, THAILAND*
[3] *Department of Mechanical Engineering, Faculty of Engineering, Rajamangala University of Technology Srivijaya, Songkhla, 90000, THAILAND*
[4] *Center for Energy and Industrial Environment Studies (CEIES), Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia 86400 Parit Raja, Batu Pahat, Johor, MALAYSIA*

*Corresponding Author: wmakatar@eng.psu.ac.th
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Abstract

Due to the energy demand for heat generation in the industrial sector, most rely on fossil fuels. However, with the limitations of decreasing resources and increasing prices, renewable energy presents an alternative to reduce dependence on fossil fuels by using biomass through the gasification process with a swirling fluidized bed gasifier (SFBG) to produce biomass gas that can be used further. This research aims to study the effect of syngas conversion by a fluidized bed gasifier, focusing on the impact of adding bed material during the conversion process, using palm oil decanter cake as biomass fuel to increase the efficiency of the syngas and to investigate the dynamic behavior of bed particles in the reactor. The research was divided into two parts: an experimental study and a numerical simulation. In the experimental study, two types of air inlet configurations were compared: updraft inlet and tangential/swirling inlet, under equivalence ratio (ER) values between 0.1 and 0.5, using silica sand as the bed material and a biomass feed rate of 3 kg/h. The CFD simulation used the Eulerian–Eulerian Multiphase Model to describe the gas and solid phase interactions inside the furnace. The simulation results showed that the addition of bed material improved mixing and temperature distribution inside the furnace, resulting in better syngas quality. The experimental comparison showed that the low heating value (LHV) of the syngas could reach an average maximum of 5.72 MJ/m^3 in the ER range of 0.5 under the tangential inlet (TI) airflow configuration, indicating the important role of bed particle dynamics and air inlet design in future furnace performance.

1. Introduction

The energy system is preferable based on the impacts of climate and climate change. To satisfy the different human needs, the system is and has been built on fossil energy, otherwise known as petroleum oil, natural gas and coal. For the weak energy security, fossil energy resources are also risky, especially with highly fluctuating prices. However, the global human population and technology, as they are, all over the ground and surface of the globe, is the basis for the increasing energy demand consumption as every technology is built energy. To facilitate the continuing development of the energy system, it will be necessary to supplement the fossil and renewable energy systems. Each will also need careful control. The simultaneous and combined systems thus used will complement the other. To meet the energy demand to develop and satisfy the needs the system of one country or region and fossil energy resources are smart and focus on weak supply. Bridging this global energy division gap will be very difficult.

Biomass, specifically residues left over from collection and production, are valuable [1], [2]. In countries with extensive agricultural byproducts and residues, the transformation of biomass into biofuels or bioenergy is increasingly important [3]-[5]. There are many ways to transform biomass, and they can broadly be classified into biochemical or thermochemical approaches. The choice of biomass conversion technique depends on a variety of factors, including the nature of the biomass, conversion costs, market demand, and the preferences of the biomass producer [6], [7]. The thermochemical conversion process known as gasification concerns how you deal with feedstocks like coal, municipal solid waste, woodchips, and wood pellets. The rationale for gasification is the production of valuable gaseous fuels referred to as synthesis gas or syngas. Based on the flow direction of syngas, feedstock gasifiers can be classified as fixed bed or moving bed, or by methods of heat generation. For biomass gasification, the aim is to transform the biomass feedstock to a gaseous fuel of a desired composition and heating value. Drying, pyrolysis, combustion, and size reduction are the gasification operations to be performed. Of primary concern are the gas composition, heating value, and syngas contamination. Biomass gasification syngas is composed of a range of gases: CO, CO_2, H_2, CH_4, and CxHy. The gas composition is influenced by the feedstock used, type of gasifier, and operational conditions including temperature, equivalent ratio of gas (ER ratio), and carrier gas [8]. Biomass gasification faces the critical problem of high tar concentration [9]-[15].

The production of tar and combustible gases during biomass gasification involves complicated interactions [16]. The thermal decomposition of lignocellulosic biomass constituents during gasification is determined by certain operational conditions such as temperature, equivalence ratio, carrier gas type, and aeration method, which are essential in determining syngas volume and quality [17]-[20]. Syngas can be employed as heat and power generation fuel depending on consumer needs. Carefully combusted syngas results in high- temperature heat generation and minimize particulate matter emissions. Furthermore, syngas can be utilized in steam and hot oil production as well as in some developed countries in syngas-fueled cogeneration systems. If syngas has the correct composition, it can be used directly in gas turbines to produce electricity. Environmentally speaking, generative biomass gasification syngas is a cleaner fuel compared to natural gas and liquefied petroleum gas (LPG) and thus offers additional advantages. The syngas gasification generally contains carbon monoxide and carbon dioxide gas, with small volumes of hydrogen and methane gas.

Bed gasifiers can be categorized into three types: fixed, fluidized, and entrained gasifiers. Fixed-bed gasifiers can be classified as downdraft or updraft gasifiers, which are also very simple in terms of construction, but tend to have lower heat energy and mass- transfer efficiencies. In response to these limitations, a moving bed gasifier has been proposed. The fluidized bed gasifier is a specific version of a moving bed gasifier. Gasifiers of this type can operate on feedstock of varying thicknesses between one millimeter and one centimeter. Fluidization of feedstock solid particles can be achieved using air, steam, or oxygen. Fluidized bed technology for biomass gasification has been widely researched and practiced primarily because of its ability to adapt to a wide range of solid fuels.

Moreover, these gasifiers maintain even temperature distributions and have compact designs. In a conventional setup, air is supplied to the gasifier through a pipe located at the bottom of the reaction chamber. The air or other fluidization medium is delivered to a fluidization distributor at the chamber bottom which is designed to lift the solid particles for fluidization. The mode of air supply has been explored as a factor affecting the combustion characteristics and the composition of syngas produced from fluidized bed gasifiers. Gasification dynamics has, in some cases, been studied using simulation tools. For instance, in the simulation conducted by Juhui et al. [21], it was shown that gas composition changes with equivalence ratio (ER) while other gas constituents remain relatively constant. As oxygen increases, it tends to control the amount of carbon monoxide and carbon dioxide present in the syngas at different ER. In another work, Naveed et al. [22] reported the air distributor design in fluidized bed gasifiers (FBG) changed the pressure drop and distribution of air. In addition, Thanh et al. [23] reported that non-reactive models of circulating fluidized bed gasifier can reliably predict the solid circulation rate during the operation of the gasifier.

The objective of this study was to investigate the effects of syngas from adding bed material and the characteristics of different air supply patterns on the combustion behavior and characteristics of syngas in a fluidized bed gasifier [24], [25]. Mixed palm oil decanter cake was used as the starting biomass material for gasification, and the effects were studied in the case of adding bed material to the biomass transformation inside the reactor (SFBG) [26]-[30]. Air is drawn in and supplied to the combustion chamber in two forms: tangential inlet (TI) and updraft inlet (UI). The raw material (Palm oil decanter cake) feed rate is kept constant at 3 kg/h. The combustion air mass from the gasifier is supplied according to a range of air-to-fuel equivalent ratios for combustion. After the experiment, data were collected to analyze the combustion behavior and characteristics of syngas, as described in this study. Its production efficiency will be studied in depth and further calibrated in future research.

2. Methodology

2.1 Experiment

2.1.1 Experimental Setup

Fig. 1, the experimental setup of this research consists of key components such as a biomass storage hopper and a screw for feeding fuel into the combustion chamber. The biomass feeding rate is set to 3 kg/h through an inverter frequency control. For the combustion air, a room temperature exhaust fan is used to directly suck air through the openings to monitor and control the air flow rate into the combustion chamber. The air flow rate inside the pipe is read through an inclined manometer. The experimental air flow rate is controlled under the equivalence ratio specified in this research. The reactor in this experiment uses a swirling fluidized bed gasifier (SFBG) design, with the air inlet pipe located at the bottom of the reactor, as shown in Fig. 2, adjacent to the ash chamber. This is because after processing, the ash falls to the bottom and is stored in the ash chamber. Thermocouples are used to measure the temperature, and they are installed at different heights of the reactor. Two types of thermocouples are used: an S-type thermocouple is installed on T1-T2 because it is the high- temperature combustion area, and a K-type thermocouple is installed on T5-T6 because it has a lower temperature. Two cyclones are installed at the syngas outlet to filter dust and tar from the syngas. A water scrubber is used to remove tar and cool the syngas before it enters the syngas analyzer. This experiment measures the properties of combustion gases such as carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), methane (CH_4), nitrogen (N_2), oxygen (O_2) and low heating value (LHV).

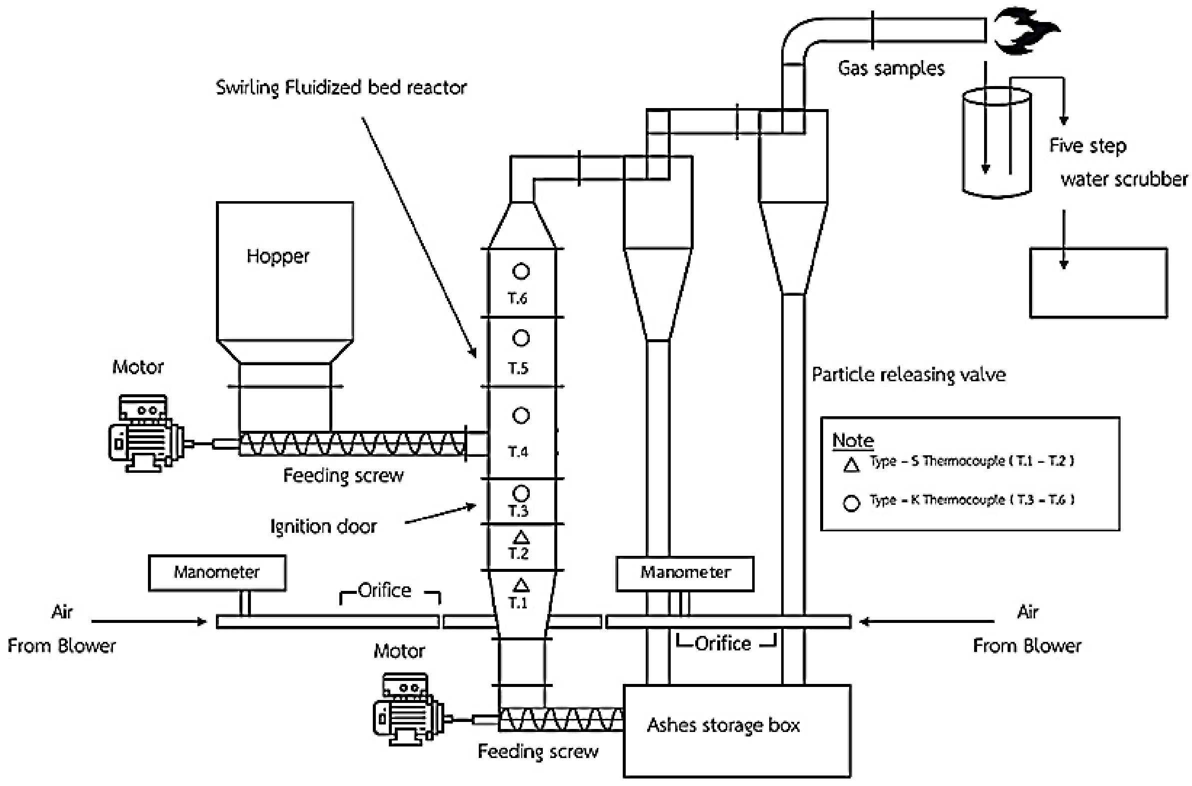

Fig. 1 *A Diagram of the experimental setup of gasification system*

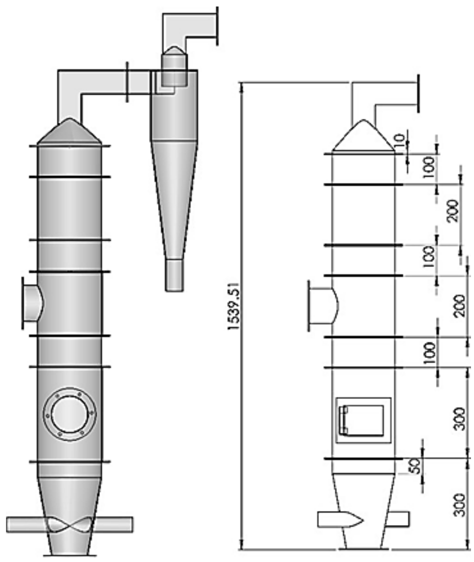

Fig. 2 *Details of gasification reactor*

2.1.2 Biomass and Bed Materials

The experimental biomass of this research was palm oil decanter cake, as shown in Fig. 3(a), with an average total size not exceeding 10 mm. It was analyzed by Proximate and Ultimate analyses, as shown in Table 1. The composition values were examined to determine the equivalence ratio range and air flow rate for the decanter. The bed material used for the decanter with biomass was silica sand, as shown in Fig. 3(b). The size of the sand was in the range of 0.1-0.45 mm.

(a) **(b)**

Fig. 3 *Feedstock (palm cake) and bed material used for feeding in the fluidized-bed gasification (a) Palm oil decanter cake; (b) Bed material (silica sand)*

Table 1 *Properties of biomass feedstock*

Properties (as received basis)	Unit	Value
Proximate analysis		
Moisture	% wt.	6.12
Volatile matter	% wt.	70.61
Fixed carbon	% wt.	17.67
Ash	% wt.	5.60
Ultimate analysis		
Carbon (C)	% wt.	47.0111
Hydrogen (H)	% wt.	6.2030
Oxygen (O)	% wt.	39.1761
Nitrogen (N)	% wt.	1.1716
Sulfur (S)	% wt.	0.1636

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2.1.3 Operating Conditions

In this experiment, the Equivalence Ratio (ER) equation is used to calculate the range of actual air mass from Eq. (1), in order to determine the range of volume and velocity ratios of air entering the gasification process, all within the scope and conditions of the work. These can be calculated from Eq. (1).

$$ER = \frac{\left(\frac{A}{F}\right)_{actual}}{\left(\frac{A}{F}\right)_{stoichiometric}} \qquad (1)$$

where $(A/F)_{stoichiometric}$ is the mass flow rate of air required for the complete combustion of biomass, which can be calculated from the biomass properties analyzed in the previous ultimate analysis. The important variables in the required equations are C, H, O, and N, which can be substituted into the equation to find $(A/F)_{stoichiometric}$, as shown in Eq. (2).

$$\left(\frac{A}{F}\right)_{stoichiometric} = \frac{m_{air}}{\dot{m}_{fuel}} = \frac{(O_2 \times 4.76) \times 30}{(C \times 12) + (H \times 1) + (N \times 14) + (S \times 32)} = 6.45 \qquad (2)$$

2.2 Computational Fluid Dynamics (CFD)

2.2.1 CFD Model

Computational Fluid Dynamics (CFD) software, ANSYS Fluent, would be used to simulate particle flow behavior inside the reactor for this research. The scope includes two types of flow simulations to compare the effects of different air flow characteristics. There are two types of air inlet pipes: up-flow air inlets and tangential- flow air inlets. As shown in Fig. 4, the direction and position of the air inlet must be set at the bottom to match the actual reactor, and there is a gas vent pipe at the top. The outlet is set to atmospheric pressure.

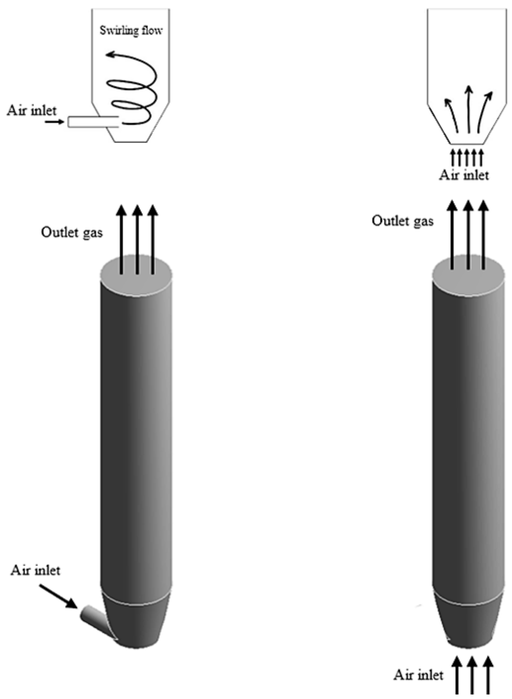

Fig. 4 *Gasification reactor model*

2.2.2 Mesh Generation and Mesh Independent Study

A swirling fluidized bed gasifier (SFBG) is simulated based on the distances and dimensions of the actual experimental setup. As shown in Fig. 5, the grid and meshing of the furnace use a Cartesian mesh structure. Refinements are made only at critical points, such as the exposed air intake and the bottom of the cone, to ensure numerical stability and precise resolution of the flow field. This can be observed in the internal cuts shown in Fig. 5. The mesh independence study was performed by comparing the results for different numbers of mesh elements, as shown in Fig. 6, ranging from 195,521 to 1,911,529 elements. It was found that the axial velocity results changed by less than 2% when the number of cells exceeded 985,369, indicating that the system met the mesh independence criterion. Therefore, the mesh with 1,563,302 elements was chosen for the simulation in this research to balance accuracy and computation time.

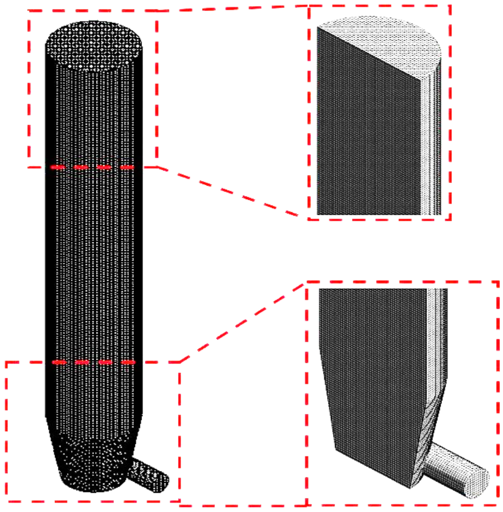

Fig. 5 *External and internal mesh of the CFD model*

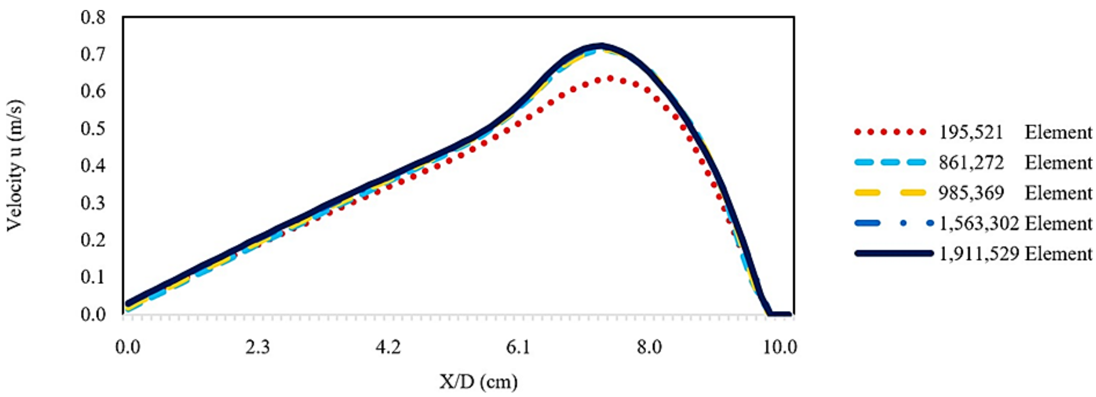

Fig. 6 *Mesh independent study*

2.2.3 Boundary Condition and Calculation

Determining the conditions and scope of this research study, as for the air inlet pipe, the velocity inlet (m/s) air input condition is determined by adjusting the wind speed value to be consistent with the air velocity value from the calculation of various air-fuel ratios (Equivalence Ratio, ER) from the previous equations that have been presented. The outlet pipe is conditioned as a pressure outlet so that air and gas can flow out freely. The wall definition is set to No-slip to prevent heat exchange between the wall and the fluid. For the multiphase model setup of this research, the Eulerian-Eulerian Multiphase model was used using the Gidaspow drag model to calculate the friction force between particles and air. And in the calculation, Transient mode is used in order to check the particle flow behavior with a time step of $1x10^{-3}$ s to obtain stable changes in the flow field in each calculation period. The pressure and velocity links use SIMPLE Algorithm, while the momentum and phase equations use Second-order Upwind Scheme to increase numerical accuracy.

3. Results and Discussion

3.1 Temperature Profile

Fig. 7 shows the temperature profile along the height of the fluidized bed gasifier axis, comparing the case without material addition and the case with bed addition. The case with bed addition is the experimental result of this research and is shown together with a comparison of the air supply patterns, namely updraft inlet (UI) and tangential inlet (TI). The experimental results showed that in the updraft inlet (UI) case, without adding bed material, the temperature inside the reactor is high at the bottom, around 500°C, with the highest temperature only at the bottom and decreasing rapidly by around 100°C when moving up the reactor axis. As a result, the reaction zone is limited to the bottom area, and a low-temperature zone is formed in the upper part of the furnace (cold zone). This results in a significant decrease in the efficiency of fuel cracking and the reduction reaction. This indicates that vertical airflow without bed material results in incomplete heat transfer and mixing between gas and fuel particles.

In the experimental results, when sand was added as bed material in the updraft inlet (UI), it was found that the temperature in the lower zone of the furnace increased, as shown in Fig. 7, and the temperature at the bottom of the furnace could be stably maintained at positions T1-T2, with the temperature in the range of 550-600°C. From the results of the temperature profile in the case of the tangential inlet (TI) side flow air inlet, which supplies air in a swirling manner, it was found that the temperature was evenly distributed in the constant temperature range of 550–600°C. In the case of the addition of co-bed material, the temperature was in the range of 320-400°C because the swirling flow of air helps to increase the mixing between air and fuel, resulting in better combustion and reduction reactions throughout the furnace volume.

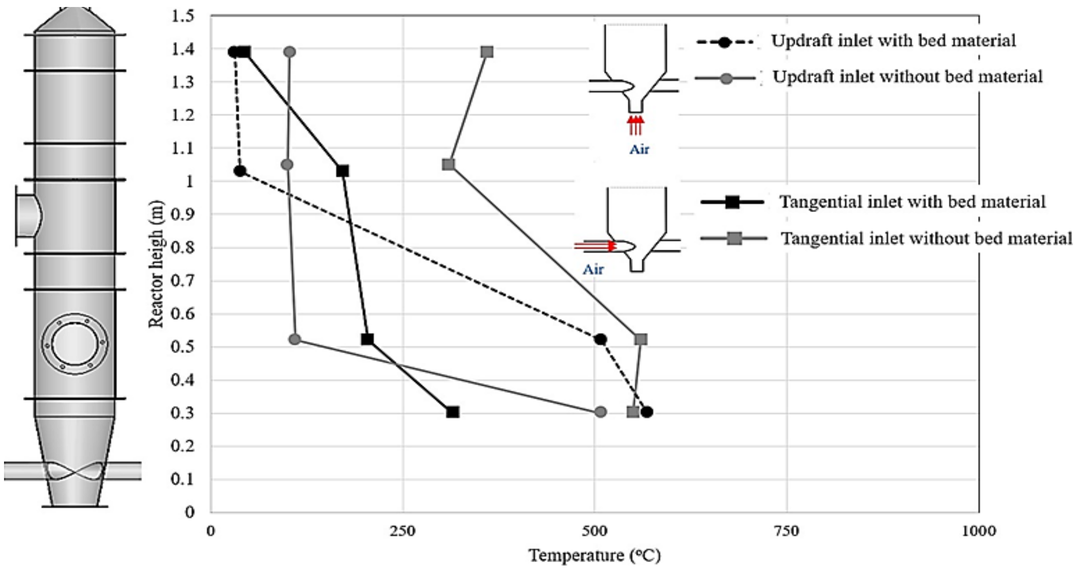

Fig. 7 *Temperature profile along the centerline of gasification reactor (experimental results)*

3.2 Syngas Composition

Fig. 8 shows the composition of synthesis gas from the fluidized bed gasification process at a 0.5 ER using fine sand in the range of 0.1-0.45 mm as bed material. The experimental results are shown for both updraft inlet (UI) and tangential inlet (TI) to compare the gasification efficiency of synthesis gas between the case without bed material addition and the case with bed material addition inside the furnace. The case with bed material addition presents the experimental result from this research. The experimental results for both cases, with and without bed material, show that bed material addition significantly affects the quality of the synthesis gas. The important synthesis gases for considering process efficiency are CO, CO_2, CH_4, and H_2, which are important components for calculating the calorific value. Fig. 8(a) and 8(b) clearly shows that the addition of bed material improves gasification efficiency in both air inlet configurations.

For the updraft inlet (UI) case without bed material Fig. 8(a), the carbon dioxide (CO_2) concentration produced was as high as approximately 20%, as shown in Fig. 8(a). Meanwhile, carbon monoxide (CO) and hydrogen (H_2) had averages lower than 10%, especially CO, which was 14% lower than CO_2. This reflects an incomplete reduction reaction and low efficiency of gas-fuel contact inside the furnace, causing most of the biomass carbon to be directly oxidized to CO_2. However, the experimental results of adding fine sand as a bed material to the furnace Fig. 8(a) showed that the CO concentration significantly increased to approximately 24.8%, while CO_2 decreased to only 8.3%, and the contents of CH_4 and CnHm decreased slightly. The results of the obtained synthesis gas indicated more efficient carbon transformation and a more complete reforming reaction.

This also indicates a good transition from combustion to gasification. In addition, the H_2 concentration increased to approximately 9.1% due to the improved heat transfer from the bed material to the biomass. The experimental results show that the addition of bed material in the UI system helps to achieve a balance between the oxidation and reduction zones, resulting in higher quality synthesis gas with lower CO_2 emissions.

In the case of the tangential inlet (TI) shown in Fig. 8(b), it can be observed that the changing trend remains in the same direction: when the bed material is added, it provides better concentrations of important synthesis gas components than the case without bed material inside the furnace. Considering the amount of CO, the case without bed material shows about 14.8%, and H_2 is about 5.5%, while CO_2 is as high as about 17%, indicating incomplete mixing of air or O_2 and fuel. Compared to the case with fine sand as the bed material, the concentrations of CO and H_2 increased by about 27.59% and 8.18%, respectively, while CO_2 decreased to7.5% and CH_4 decreased significantly in Fig. 8(b). This result reflects that the tangential inlet (TI) case results in more efficient heat exchange, and the particle distribution increases the contact area between the gas and fuel particles. This leads to a more pronounced reduction reaction than in the updraft inlet (UI) case. Comparing both the updraft inlet (UI) and tangential inlet (TI) under the same operating conditions (ER= 0.5, fine sand 0.1–0.45 mm), it was found that the combination of fine sand as bed material and TI inlet significantly improved the gasification process efficiency, yielding synthesis gas with higher CO and H_2 concentrations while reducing CO_2 generation. It also demonstrated more efficient energy exchange and particle circulation within the bed than the UI inlet, confirming the advantages of swirling flow in the development of fluidized bed gasifier with better and more stable gas fuel quality.

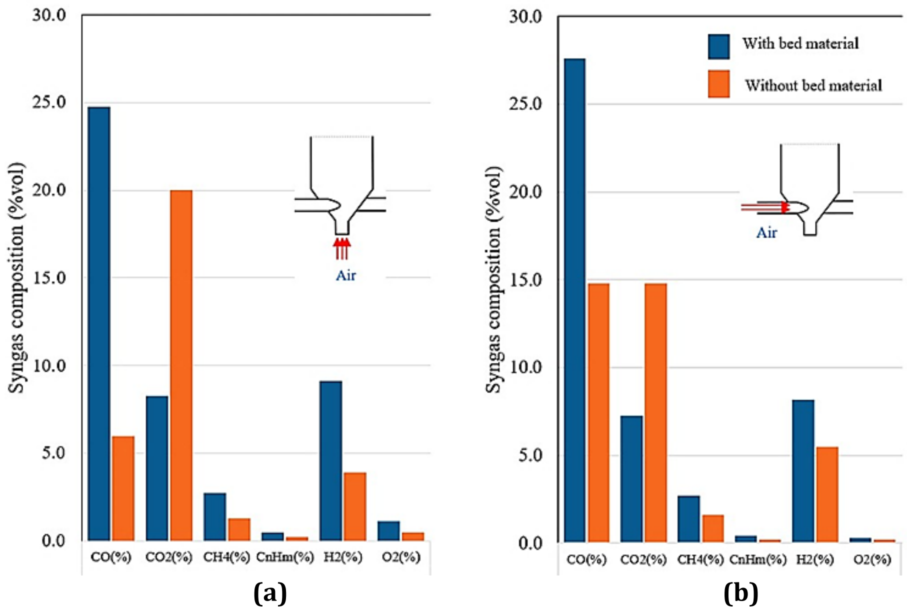

Fig. 8 *Gas composition of syngas from fluidized-bed gasification (experimental results) (a) Updraft inlet; (b) Tangential inlet*

3.3 Heating Value of Syngas

Fig. 9 shows the low heating value (LHV) of synthesis gas obtained from the gasification process in a fluidized bed gasifier. The results show the maximum efficiency of the swirling fluidized bed gasifier in the equivalence ratio (ER) range of 0.5 using fine sand of size 0.1–0.45 mm as bed material. The experimental results are compared between the case without adding bed material and the case with adding bed material. The calibration results are divided into two air inlet flow patterns: updraft inlet (UI) and tangential inlet (TI). The experimental results, as shown in Fig. 9, found that adding bed material significantly increases the LHV value of synthesis gas compared to the case without bed material. The LHV value increases from 4.10 MJ/Nm^3 to 5.72 MJ/Nm^3 for the TI air flow pattern and from 4.37 MJ/Nm^3 to 5.54 MJ/Nm^3 for the UI air flow pattern.

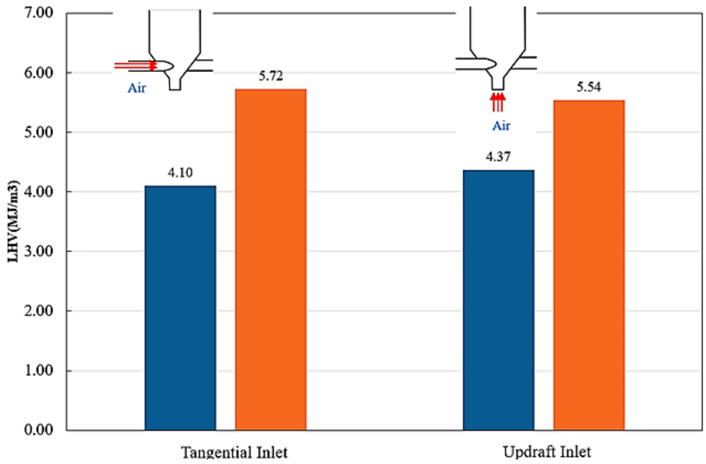

Fig. 9 *Lower heating value (LHV) of syngas (experimental results)*

The increase in LHV can be explained by the behavior of gas composition and temperature distribution inside the furnace, as shown in the previous experimental results. That is, when the bed material is added to the system, the amounts of CO and H_2 gases increased significantly, while CO_2 and CH_4 gases decreased in both air-feeding schemes (as shown in the previous Fig. 8(a) and 8(b). The increase in CO and H_2, the main components with high calorific value, directly affected the increase in the LHV of the synthesis gas, while the decrease in CO_2, the product of complete oxidation, showed that the combustion process was controlled within an appropriate range, resulting in more energy being stored in the form of syngas.

3.4 Dynamic Behaviour in the Gasification Reactor

Figs. 10 and 11 show the 2D and 3D fluidization simulation results for the updraft inlet at ER = 0.5, with sand as the bed material. It is observed that the upward or vertical air supply from the furnace bottom causes fluidization only in the core region of the furnace during the early period (observed in the time steps of t = 0-0.3 s from Fig. 10 and 11(a-c)), while the area near the walls is almost motionless (indicated by the blue region of low solid fraction), indicating limited vertical channel flow (solid fraction around 0-0.1). This flow pattern causes the particles in the bed to move only vertically without sufficient lateral swirling (observed in the time steps of t= 0.45–0.9 s from Figs. 10 and 11(d–g)), resulting in non-uniform heat distribution.

On the other hand, the tangential inlet air intake from Figs. 12 and 13 shows an early onset of swirling flow (observed at time steps t = 0.3–0.6 s in Figs. 12 and 13(c–e)), which induces radial convection of particles from the tangential inlet air that continues throughout the simulation time (observed at time step t = 1.2 s in Figs. 12 and 13(i)). This swirling flow results in thermal uniformity and stronger gas–solid mixing, leading to longer residence times for particles and gas in the reaction zone and promoting endothermic reactions such as CH_4 cracking and hydrocarbon reforming, which significantly increase the CO and H_2 ratios and decrease CO_2.

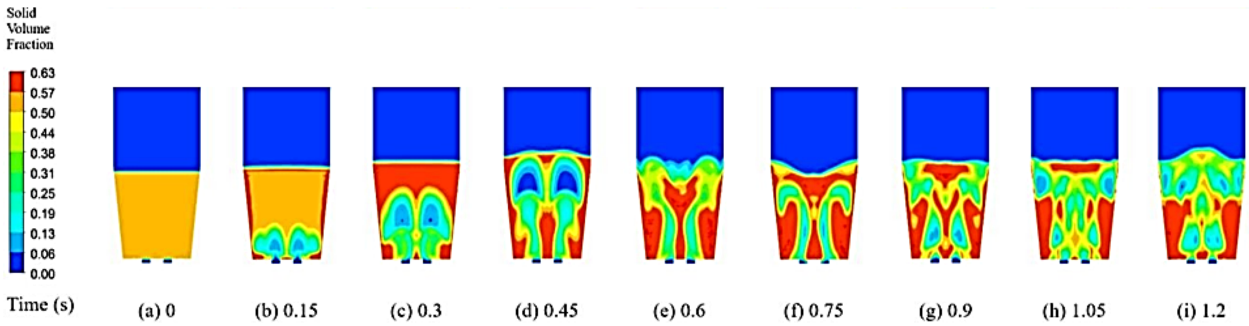

Fig. 10 *2-D Fluidization for the case of updraft inlet, ER=0.5, silica sand bed material (simulation results)*

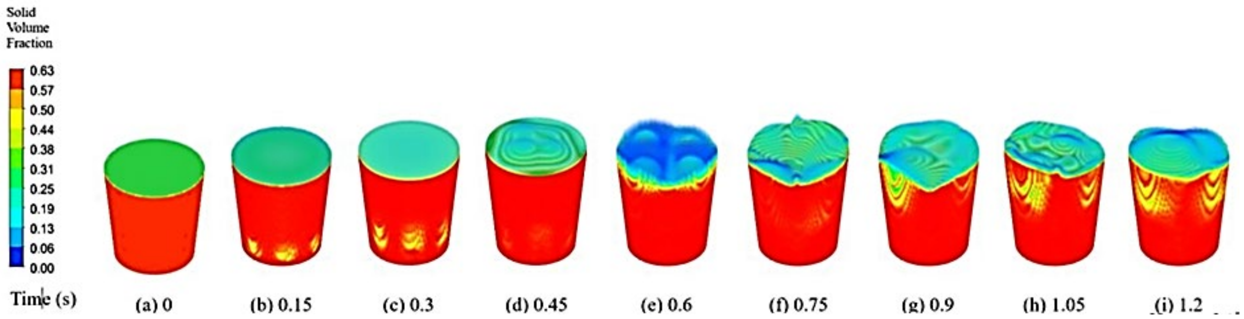

Fig. 11 *3-D Fluidization for the case of updraft inlet, ER=5, silica sand bed material (simulation results)*

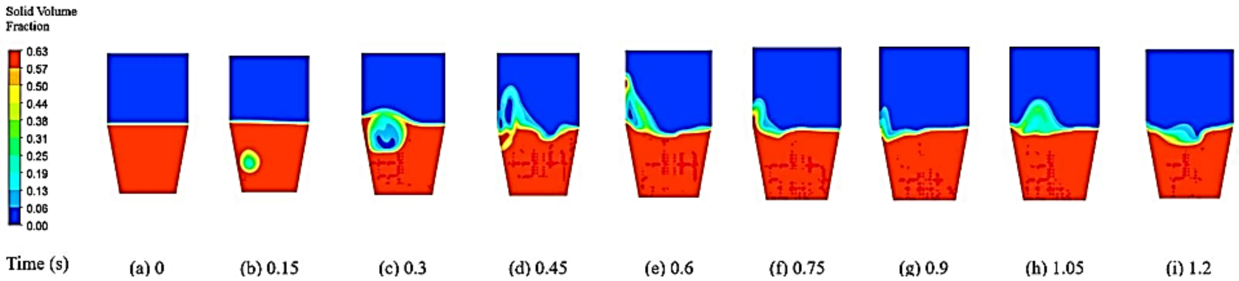

Fig. 12 *2-D Fluidization for the case of tangential inlet, ER=0.5, silica sand bed material (simulation results)*

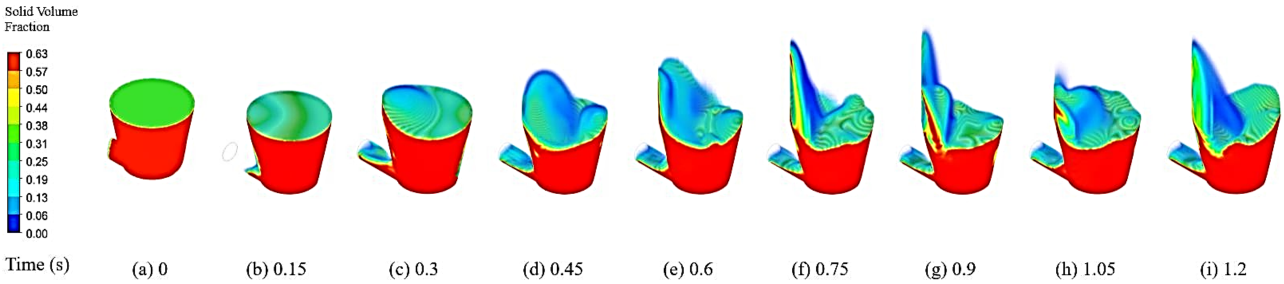

Fig. 13 *3-D Fluidization for the case of tangential inlet, ER=0.5, silica sand bed material (simulation results)*

4. Conclusions

This research studies the effect of fuel gas properties on the bed material filled with sand, with updraft and lateral flow characteristics of swirling air flow. This study is conducted in conjunction with Computational Fluid Dynamics (CFD) simulations in the form of particle dynamic behavior. The results of the research are summarized as follows:

1. Experimental results from the addition of fine sand as a bed material improved gasification efficiency in both flow modes (UI and TI) and also improved gas-solid mixing and temperature uniformity, leading to improved reduction reactions. Gas analysis showed higher CO and H_2, lower CO_2 and CH_4, and higher LHV values.
2. The results of the comparison of air flow characteristics between UI and TI found that the side inlet (TI) inlet system has higher efficiency than the updraft inlet (UI) because the TI flow pattern increases heat transfer more effectively through the stable swirl of air and particles and maintains a uniform temperature along the height of the furnace. This results in higher quality synthetic gas with an average LHV value of 5.72 MJ/Nm^3, while the UI system has a value of only 5.54 MJ/Nm^3.
3. The CFD simulation results show that the flow behavior of air and particles inside the furnace is consistent with the experimental results. The UI air flow exhibits a pattern that limits the fluidization of particles to the center of the furnace, resulting in incomplete mixing and low heat transfer. Meanwhile, the TI air flow exhibits a swirling flow that evenly distributes particles and temperature, resulting in a more continuous and stable reaction zone.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors are responsible for the study conception, research design, data collection, data analysis, result interpretation and manuscript drafting.

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