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The Effect of Air Equivalent Ratio on Combustion and Gasification Process Characteristics of Oil Palm Biomass in Fluidized Bed Reactor

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ABSTRACT

This study investigated the effect of air equivalent ratios (ERs) (0.1-5) on the temperature distribution in the fluidized bed reactor during gasification and combustion process. The cylindrical reactor with the diameter of 20 cm and height of 150 cm was used in this study. The conical shape connector was installed at the bottom of the reactor for different air supplying patterns, including tangential flow and up-flow. The mixed oil palm cake was used as a feedstock. The temperature distribution in the reactor during combustion and gasification process was observed by applying the numerical calculation using ANSYS software (Ver.19.0, Fluent) with 3D model. The effect of air supplying patterns and air equivalent ratios were then investigated. The results showed that the temperature distribution obtained from simulation was not consistent with the experiment results for an up-flow air supplying method. In the case of tangential air inlet, the results from simulation were similar to the experimental results. Consequently, these results will be the guideline for further studies of biomass gasification and combustion using fluidized bed gasifier with different inlet air patterns and ERs.

1. Introduction

Currently, there has been much research [1-4] on using biomass from agricultural and industrial activities as a source for biofuels and bioenergy due to the reduction of conventional fossil fuel, as well as the negative impacts such as climate change, global warming, and emission from fossil fuels. Thus, utilization of renewable energy resources like solar, wind, hydro and biomass is the way to overcome these issues. Biomass from agro-industries has high potential for energy applications in some countries, like Thailand. The oil palm biomass is available in the southern region of the country.

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This biomass can be converted into biofuels or bioenergy by several processes such as biochemical, thermochemical, and physical processes. The choice of one process among the options is market-driven. Thermochemical processes such as torrefaction, pyrolysis, gasification and combustion of biomass are the popular routes for biofuels production in different forms (solid, liquid and gas). Gasification is the partial oxidation process of feedstock at an elevated temperature (700-1500 °C) to produce synthesis gas (syngas). This gas mainly contains CO_2, CO, CH_4 and H_2. The quantity and quality of syngas depend on many factors such as gasifier type, biomass type and composition and operating parameters (temperature, ER, oxidizer type, etc.). The syngas from biomass gasification can be used for replacing the natural gas (NG) and liquefied petroleum gas (LPG) for both heat and power generations. Although the biomass gasification process has been developed and studied, the research in this field is still challenging due to the nature of biomass and demand of users.

In the case of combustion, it is complete oxidation process of fuel and oxygen or air at high temperature [5,6] to generate heat. For solid fuels like coal or biomass, it is burned to generate heat from the formation of CO_2, H_2O, SO_x, and No_x [7]. The thermal energy or heat from combustion is widely applied for many purposes such as hot gas/air generation, hot oil generation and steam generation. The steam generation is the conventional process both for industry and power plant. Combustion of biomass for steam generation in Thailand is widely applied with different combustion systems. Combustion of biomass is well known that it is a mature technology. However, study of biomass combustion is still challenging. This is because the combustion behavior of each biomass source is different.

From the concept of gasification and combustion, it is seen that the operation and target are relatively different. The thermal and chemical reactions during the gasification inside the reactor cover several sub-processes, including (1) drying, (2) pyrolysis, (3) combustion and (4) reduction [8–9]. Operation of the gasifier to obtain suitable condition with maximizing gas yield and good gas components (CO, H_2, and CH_4) is a challenging task. This is because biomass gasification is expected to obtain high yield and quality (high heating value and low tar content) of syngas. This syngas is preferred for further combustions in combustion chamber for heat generation, and combustion in gas engine for power generation [10, 11]. Consequently, observing and controlling the reactor's temperature is an essential aspect of its operation. The temperature during the process can be directly measured by using the temperature probe or by predicting via the simulation. The simulation by computer software related with heat and mass transfer, and fluid dynamics, like computational fluid dynamics (CFD) is a powerful tool for solving many engineering problems. The simulation method helps to save time and cost of the engineering projects. Based on the previous studies, the observation of temperature inside the reactor during biomass gasification and biomass combustion has been studied. However, the study related to simulation by using CFD are not much available, particularly the temperature profile inside fluidized bed reactor with different air supplying configurations. The previous studies [12,13] indicated that the reactor with the tangential air supplying to create a swirling flow pattern improved the heat and mass distribution. However, these studies were only investigated at small range of equivalent ratio (ER). The previous investigations did not observe the temperature distribution during the gasification and combustion processes inside the reactor.

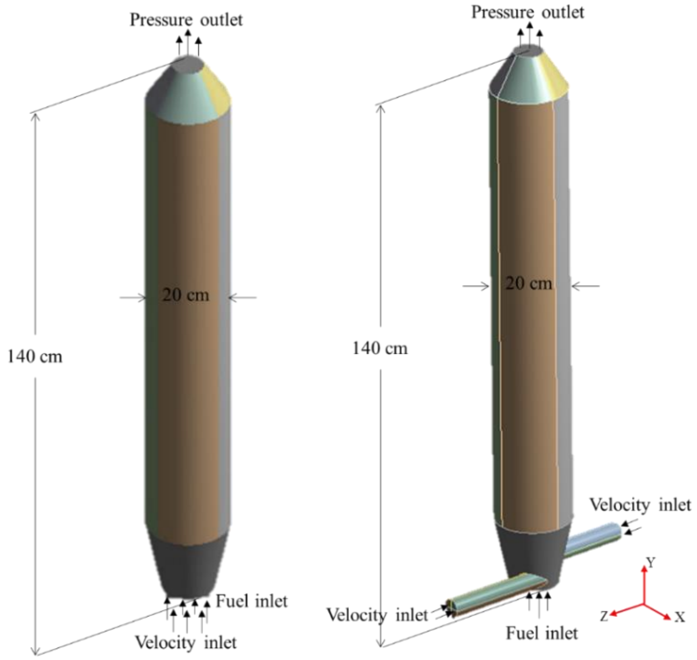
Therefore, the aim of this study was to investigate the temperature distribution inside the fluidized bed gasifier while the equivalent ranged from 0.5 to -5.0, using various air supplying patterns of the oil palm biomass gasification and combustion processes. The study was performed by CFD simulation and experiment, and then the results were compared.

2. Methodology

2.1 Numerical Simulation Model

2.1.1 Computational model and grid generation

The shape and dimension of the reactor for biomass gasification and combustion for 3D model simulation with the commercial CFD program (ANSYS, Fluent) is shown in Figure 1. The diameter (D) and height of the reactor was 20 cm and 150 cm, respectively. The inlet air position of the reactor was located at the bottom. There are two types of inlet air supplying patterns, including up-flow and tangential flow. In the case of up-flow as shown in Figure 1(a), the nine air inlet pipes with a diameter of 22 mm were used to distribute the air at the inlet area. The tangential inlet air supplying method as shown in Figure 1(b), the inlet air pipe with an inner diameter of 46.8 mm was installed as double inlet to create swirling flow. The boundary conditions for the simulation is summarized in the Table 1.



(a)Updraft inlet (b) Tangential inlet

Fig. 1. Computational model and its boundary conditions

In this study, the grid generation for the reactor domain was a rectangular grid as shown in Figure 2. The grids were modified at specific positions based on the air velocity which depends on a grid size dependence test obtained from previous studies [14,16]. The generated grid had approximately 1.8 million elements.

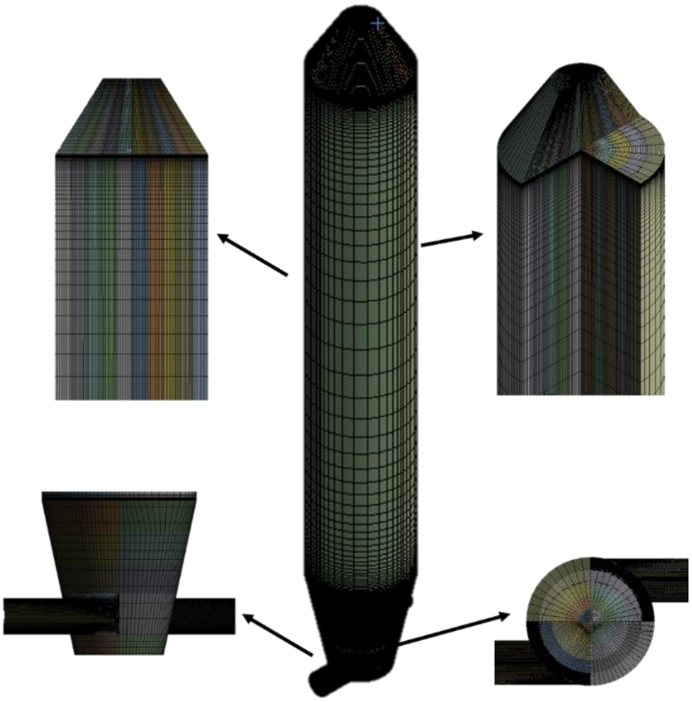


Fig. 2. Generated rectangular grid for the numerical model

Table 1
The details of boundary conditions

Boundary at	Specified
Air inlet	Velocity at inlet (From Table 2)
Air outlet	Pressure at outlet (1 atm)
Fuel inlet	Fuel feed rate 3 kg/hr
Surfaces of reactor	Solid walls

2.1.2 Calculation method and algorithm

The Reynolds-averaged Navier–Stokes equations were applied to solve the problem under specified boundary conditions, following the calculation procedure. The K-epsilon turbulence model was used to solve the numerical internal flow simulations. It was used due to the accuracy of the forecast for internal flow simulations with low cost of computation method. The calculation method for combustion was the Discrete Ordinate (DO) model. It was used in the section of the radiation model. The species transport model was performed based on the proximate and ultimate analyses results of kernel mixed palm cake.

The SIMPLE algorithm with an upwind scheme was used by separating into two different upwind plans. The first-order upwind scheme was used for turbulent kinetic energy and turbulent dissipation rate, and discrete ordinates. The second-order upwind scheme was the calculated pressure, velocity, and temperature. The simulation was performed with the residual of variables less than $1\text{x}10^{-4}$, the iterative equation was also converged.

2.1.3 Numerical parameter

The cross section area of inlet air pipe both up-flow and tangential flow, as well as air mass flow rate were maintained as same value. Thus, the inlet air velocity was the same parameter in both conditions as shown in Table 2. The air velocity of each equivalent ratio was presented as a simulation. The feed rate of biomass was fixed at 3 kg/hr.

Table 2
Numerical parameters

Equivalent ratio (ER)	Air velocity for configurations (m/s)
0.1	0.123
0.3	0.369
0.5	0.615
0.7	0.861
1	1.230
1.4	1.722
2	2.460
3.3	4.058
5	6.149

2.2 Experiment

2.2.1 Experimental setup

The experimental apparatus is shown in Figure 3. The diameter and height of the reactor were the same size with specification in numerical studies. The inlet air pipe of combustion chamber was designed to be tangential form with a double inlet pipe which had an inner diameter of 4.68 cm.

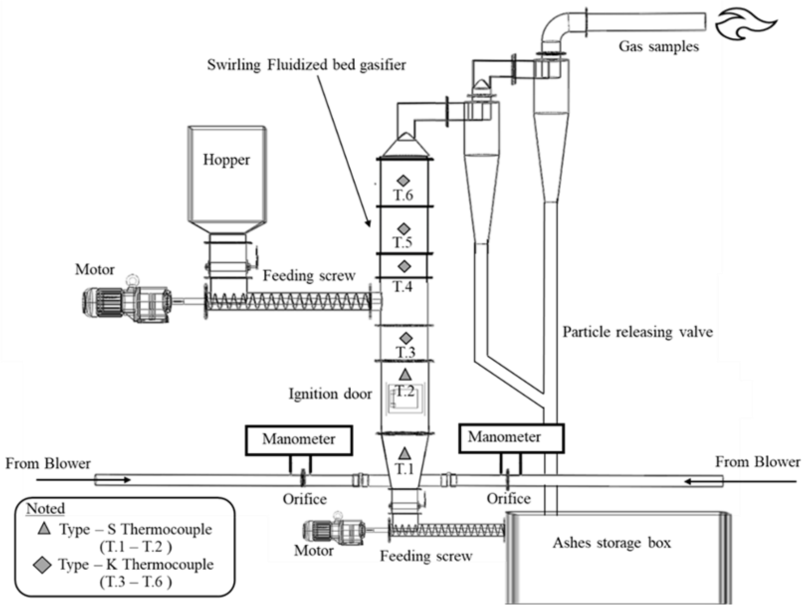


Fig. 3. Schematic diagram of fluidized bed reactor

An orifice equipment was used to measure the flow rate of the air supplied by a blower. The air was supplied into the reactor via the double inlet pipe. A screw feeder was used to supply the feedstock into the reactor. The feed rate of feedstock was controlled by adjusting the speed of the motor driving the screw feeder using an inverter. At beginning of the process, gasoline was used as fuel to start the combustion of biomass in the reactor. The gasification process was occurred after starting burning the biomass at specific conditions. The temperature inside the reactor was increased following the quantity of supplying air. The synthesis gas flowed from reactor chamber to the cyclone, which eliminates the solid particles. Temperature changes along the reactor height were measured using S-type (for T.1 and T.2) and K-type (for T.3, T.4, T.5, and T.6) thermocouples, and recorded with a data logger (HIOKI, Model LR8400). The insulator for high temperature systems (KAOWOOL, ASK-7912-H 8P Blanket 1,400 ^{o}C) was used around the reactor to reduce the heat loss.

2.2.2 Experimental parameter

In this study, the mixed palm kernel cake, which was a by-product from crude palm oil production process was applied as feedstock. The size of this feedstock was lower than 10 mm. Table 3 presents the ultimate and proximate analyses of mixed palm kernel cake [16]. They were analyzed using the CHNS/0-2000 and MACRO TGA. The mass flow rate of air was controlled to obtain the desired equivalent ratios (ER) 0.1, 0.3, and 0.5 for gasification and above 1 for combustion process. The feed rate of feedstock was fixed at 3 kg/hour.

Table 3
The characteristics of mixed palm kernel cake used in this work [16]

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

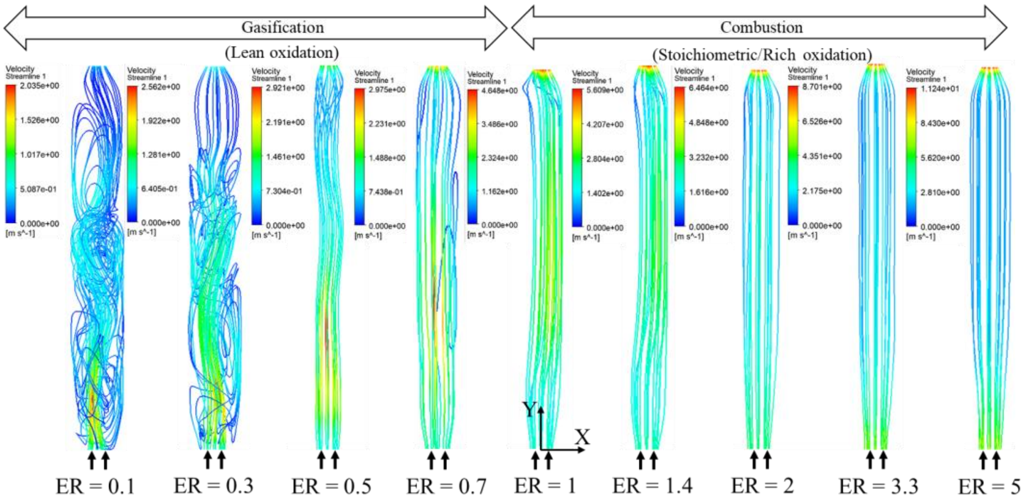
3. Results

3.1 Numerical Studies of Fluidized Bed Reactor

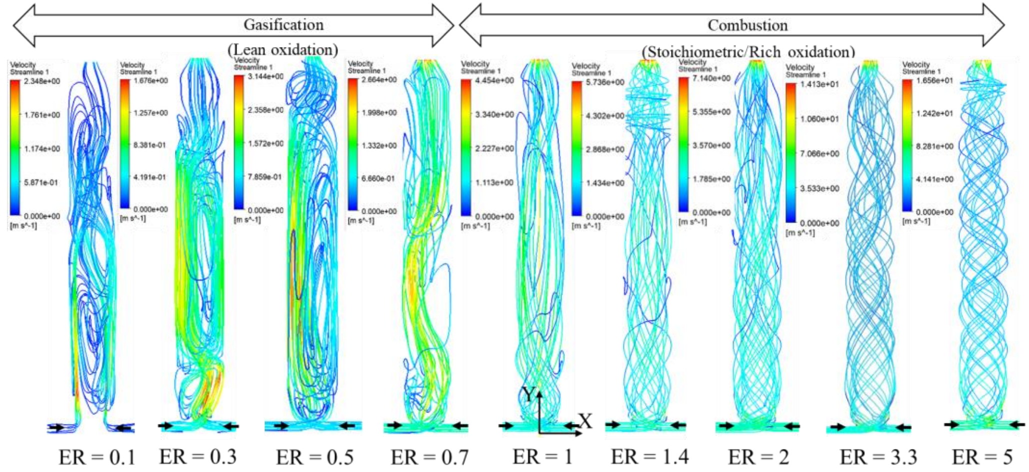
Figure 4(a) and (b) depict the results from simulation by showing the streamline of air flow inside the reactor for the case of updraft inlet air and tangential inlet air, respectively. It can be seen that the ascending velocity streamline for an updraft inlet air (Figure 4(a)) can be divided into two groups, corresponding to the ER ranging from 0.1 to 0.3, and the range of 0.5-5. At low ER (0.1-0.3), the air velocity was also low in this section, thus the streamline pattern of the air was the swirl inside the reactor. When the ER was increased from 0.5 to 5, the streamline of the air was uniform pattern, and the flow direction was clear. This corresponded to the value of Reynold number of fluid flow. This result was similar to the previous studies [14-16] for correcting the simulation at beginning step.

In the case of tangential inlet air as shown in Figure 4(b), the streamlines of the air were clearly different from up-flow inlet air. It is seen that the air flow pattern inside the reactor chamber was turbulent for all equivalent ratios. However, it is observed that the development of inlet air velocity led to be more clear air streamlines. At ER of 0.1-0.7, one-side turbulent flow pattern can be seen before flowing out the reactor. When the ER was 1, the air flow with swirling pattern occurred with symmetry on both sides. As observed, the bottom section of the reactor had a distinct swirl. In the case of higher ER, the level of the swirling pattern was clearer, indicating the flow pattern as swirling.

This flow pattern indicates the feasibility for mixing the solid particles inside the reactor for improving heat and mass transfer during the reaction of combustion and gasification.



(a) The updraft inlet air

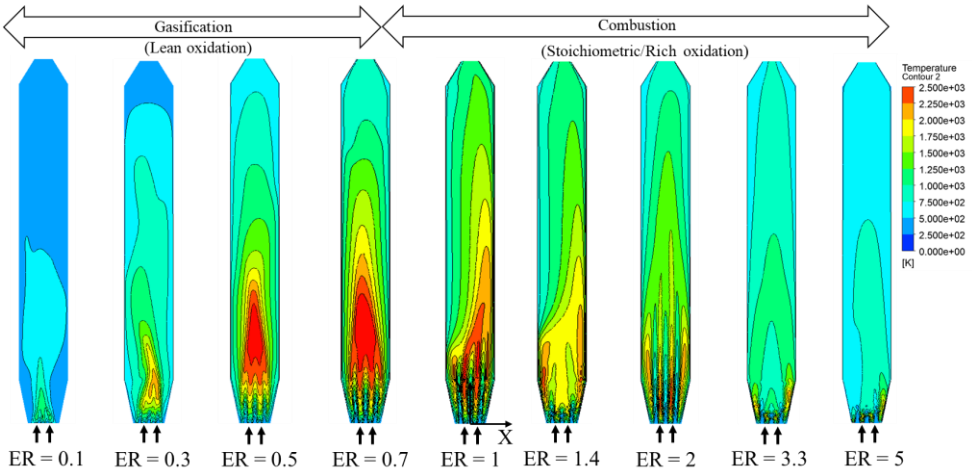


(b) The tangential inlet air

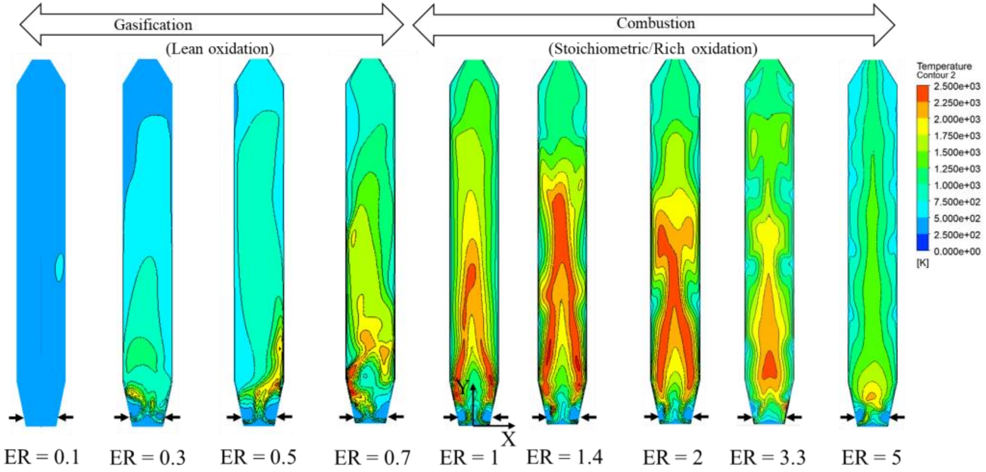
Fig. 4. The streamline in fluidized bed reactor

The temperature contour of the updraft inlet air and the tangential inlet air is shown in Figure 5. With an updraft inlet air method as shown in Figure 5(a), it was found that the maximum temperature was reached at ER of 0.7. The pattern of this contour indicated combustion at the reactor's center. The contour pattern at ER from 0.1 to 0.5 was similar to ER of 0.7. However, the temperature was slightly reduced, depending on the ER. When the ER was increased above 0.7, the higher air velocity affected the temperature distribution, resulting in lower combustion.

In the case of tangential inlet air (Figure 5(b)), it shows that the maximum temperature was achieved at ER of 1.4. With this air supplying pattern, the combustion zone started at the reactor's side, followed by the coordination in the middle of the reactor. As compared to an updraft inlet air, a large combustion zone was created in this case. Furthermore, the temperature contour of ER at 1 and 2 was similar to the temperature pattern as ER of 1.4. At ER lower than 1, it was found that the temperature contour presented on one side of the chamber before dissipating to around the chamber. Consequently, it is possible to control the temperature during the gasification process. Moreover, the observation indicated that at ER of 0.1, the temperature contour was clearly steady along with the height of the reactor. There was no optimization for continuous combustion. This is because the burning in this case was slow. An increase in ER more than 2, the combustion was not complete due to the air velocity was relatively high, leading to very low interactions with the solid particles (biomass) within the specified zone.



(a) The temperature contour of updraft inlet



(b) The temperature contour of tangential inlet

Fig. 5. The temperature contour along the reactor

Figure 6 shows the temperature profiles at the center of the reactor. This result was calculated by using an equivalent ratio from 0.1 to 5. As depicted by the dashed and straight lines, the results from updraft inlet air and the tangential inlet air were compared. At low ER (0.1-0.7), the operation with updraft inlet air provided a higher temperature than the tangential inlet air. But, the operation with tangential inlet air led to higher temperature compared to the updraft inlet air at ER of 1-5. These results indicated the type of the process, which is gasification and combustion. At low ER, the process was gasification with the conventional temperature range of 450-800 °C. The turbulent flow pattern of the tangential inlet air with low ER was resulted in a small zone maximum temperature in the dimension range (Y/D) from 0 to 1. Above this range, the temperature was reduced when the gasification process was more progressed. Consequently, the operation of the reactor with tangential inlet air is challenge for producing the syngas.

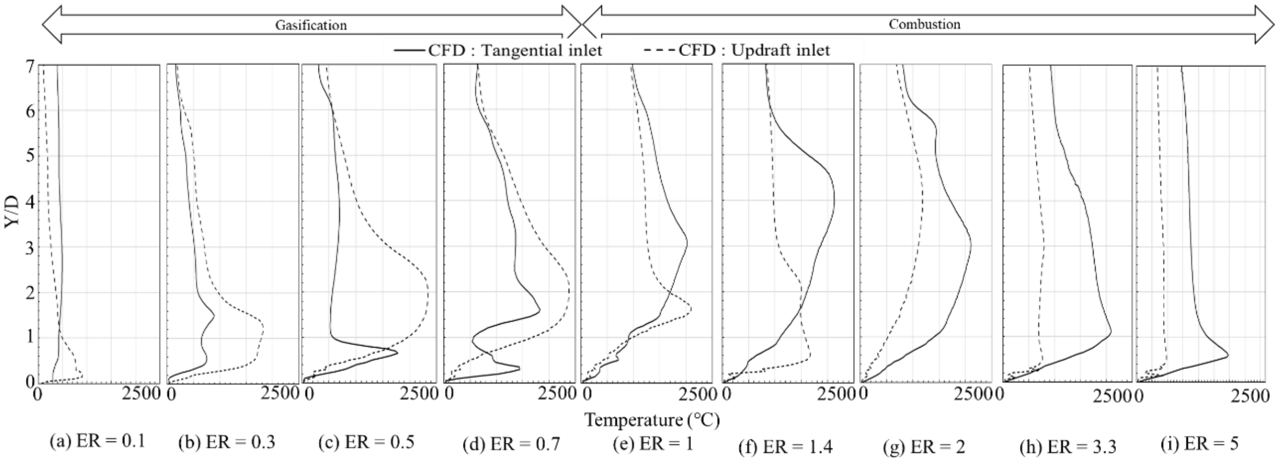
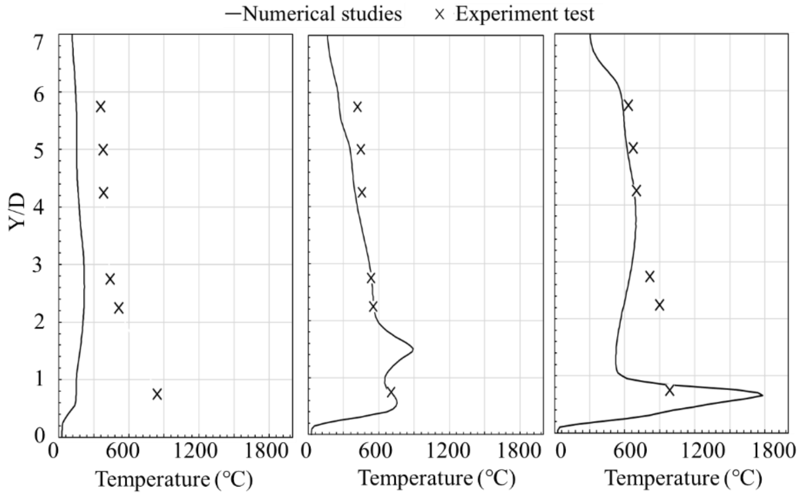


Fig. 6. The temperature profiles along the center of reactor

3.2 Numerical and Experiment Studies of Fluidized Reactor

Based on the obtained results, they indicated that the reactor with tangential inlet air has a potential for further development. This is because this reactor provided the swirling air flow pattern. This flow pattern may help to improve the reaction inside the reactor, resulting in better syngas yield and quality. The finding of this study also shows that this operation is seen to be effective way for the gasification process (low ER range). Thus, in order to confirm the simulation results the experiments were performed. Figure 7 depicts the temperature profiles along the reactor height obtained from simulation and experiment of the operation with the tangential inlet air, which was mentioned for the gasification process. They were compared at ER ranging from 0.1 to 0.5. The corresponding ratio of ER at 0.1 is seen in Figure 7(a). The temperature profiles obtained from the experiment and simulation are different. This may be because of the lowest mass flow rate of inlet air and the possibility of continuous combustion. The lowest temperature was observed at ER of 0.1 case. The highest temperature inside the reactor was 850 ^{o}C due to the combustion in a small zone, which occurred at position of Y/D of 1.25. The maximum temperature at ER of 0.3 (Figure 7(b)) was located at Y/D of 1.2 m height, while the simulation provided the result at Y/D of 1.4. It indicates the small difference between simulation and experiment. In the case of ER of 0.5 (Figure 7(c)), the maximum temperature obtained from the simulation occurred at Y/D of 0.75 m, while the experiment indicated at position of Y/D of 1.25. Thus, the further study related to this operation needs to be explored.



(a) ER = 0.1 (b) ER = 0.3 (c) ER = 0.5

Fig. 7. The temperature profiles along the reactor height for tangential inlet air (Results from simulation and experiment)

4. Conclusions

The study of temperature distribution and air flow pattern inside the fluidized bed reactor for gasification with different air supplying methods at various ERs by simulation and experiment was carried out. It can be concluded that the temperature profile of an updraft inlet air showed the basic pattern of flow during gasification and combustion processes, confirming the target of simulation. When the flow pattern of inlet air was changed as tangential inlet air, the obtained results replied the interesting temperature and velocity profiles during the gasification process at equivalent ratio of 0.1-0.7. The trend of temperature profile from simulation and experiment for tangential inlet air at ER of 0.1–0.5 were relatively similar. This result indicated that the operation of the gasification process at low temperature and low equivalent ratio is possible. Consequently, the study of biomass gasification using fluidized bed gasifier with tangential inlet air method needs to be explored.

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