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Design of a Lab-Scale Two-Stage Rice Husk Gasifier

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Abstract

Rice is a major product in Thailand and a large quantity of rice husk are generated annually in the rice milling industries, which can be used for energy exploitation. A commercial 400 MWe, two-stage gasifier has been constructed in Lopburi province using rice husk as the fuel. It is necessary to perform a further development and study of the optimization conditions to achieve a desired operating of the plant. A design procedure was developed for a 50 kWth lab-scale gasifier, and the calculations were made based on the essential parameters such as volumetric flow rate, minimum fluidized velocity, residence time to find out the dimension parameters of the reactor. On the basis of the air supplied rate, the dimensions of the first stage was calculated to provide a sustaining condition of the fluidization. The calculated diameters and heights of the lower part and upper part of the first stage were found to be 0.09, 0.13, 0.50, and 0.50 m, respectively. The height of gasification and char reduction chamber in the second stage was estimated to be 1.40 m and the calculated throat diameter was 0.10 m, whereas, the height of the char bed was variable. This design can facilitate varying parameters such as equivalence ratio, superficial velocity, and temperature. The optimization design is obtained from the experiments and from the theoretical and experimental information available in the literature.

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Keywords: Biomass gasification; Two-stage gasification; Bubbling fluidized bed; Tar; Equivalence ratio

1. Introduction

The energy demand in industries and households is rapidly increasing. The majority of energy uses are fossil fuels such as coal, petroleum and natural gas. The consumption of fossil fuels causes serious environmental problems. Therefore renewable energy is an alternative energy source that can be

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substituted for fossil fuels. Biomass is the most common type of renewable energy and its energy utilization is environmental friendly. Because the contents of sulfur and nitrogen in the biomass waste are lower than those in fossil fuels, and furthermore the carbon dioxide emitted to the atmosphere is taken up by plants for their growth.

Thailand is an agricultural country that produces a huge agricultural output. Agricultural residues such as rice husk, straw, bagasse, palm oil waste, wood waste etc. are abundant renewable energy resources. In 2009, about 60-90 million tons of agricultural residues were produced. Of these, about 65-70% was unused. The surplus biomass can potentially contribute to 2,000-3,000 MW of electric energy [1]. Therefore Thailand has a potential for using agricultural residues for energy production.

Biomass utilization as a solid fuel can be used to generated electricity, heat, liquid fuels, or production of modern energy. However, there are many drawbacks from its undesirable properties. In term of physical properties, due to its low bulk density leading to huge storage space requirements, difficulty in handling and high transportation costs. The porous structure is easy to absorb moisture and has a high moisture content. This property decreases its heating value and needs pretreatments before utilization. In term of chemical properties, biomass has carbon content lower than fossil fuels such as coal. Some biomass types has a high ash content that may cause problems in combustion devices due to ash fusion inside at higher temperatures [2].

Biomass can be converted to energy via thermochemical and biochemical routes [3]. Gasification is one of the thermochemical processes in the presence of controlled air. It is the conversion process of solid, carbonaceous fuel into combustible gas mixture which contains varying amounts of carbon monoxide, and hydrogen, normally known as synthesis gas. This gas can be burned directly in a furnace or internal combustion engine or gas turbine for heat or electricity generation. During biomass gasification, tar formation is one of the major problems that must be dealt with because it blocks and fouls the equipment such as the pipes and valves. To overcome this problem, the two-stage gasification system is introduced that the tar contained in the gas is cracked under high temperature, partially oxidized, and removed subsequently. A two-stage gasifier is named because the pyrolysis process and char gasification are separated into two different independent reactors [4].

The objective of this work is to design the related parameters associated with a lab-scale (50 kW thermal) two-stage gasifier.

Nomenclature

Ar	Archimedes number
d_p	diameter of particle (kg.m^{-3})
g	acceleration of gravity, 9.81 (m^2.s^{-1})
HHV	high heating value (MJ.kg^{-1})
LHV	low heating value (MJ.kg^{-1})
ρ_f	gas density (kg.m^{-3})
ρ_s	particle density (kg.m^{-3})

2. Methodology

In order to design the two-stage gasifier, the information available in the literature and also the experiments of other studies are used. A two-stage gasifier consists of two parts. The first part is pyrolysis which is designed as bubbling fluidized bed. The second part is partial oxidation of gas products from pyrolysis and char in the top and gas reduction in the bottom which is designed as downdraft gasifier. The dimension was calculated separately for each one of the two-stage gasifier. Also, the related parameters essential for the design are considered such as fluidization velocity, equivalence ratio and residence time.

3. Results and discussion

3.1. Fuel characteristics

The characteristics of the rice husk considered in the study are on the basis of the proximate and ultimate analysis, the calorific value and the bulk density of the fuel shown in Table 1. Oxygen content was calculated by difference.

The result of the table shows that the rice husk has high volatile matter contents (63.7% d.b.) and low bulk density (120 kg/m^3). The rice husk is easier to ignite and to burn than coal because of the high volatile matter. The low density of rice husk complicates its transportation, storage and processing. As consequence of the low density of rice husk, it is necessary to use additional particle bed (in this study 250-micron-silica sand is used) to protect the problem of channeling.

Table 2 shows the main elemental components of rice husk ash. The main component is silicon (94.81% as SiO_2), follow by potassium (2.99% as K_2O) and calcium (0.74% as CaO). The presence of such elements as alkali metals (Na and K) and phosphorous in the fuel could have a detrimental effect on the melting properties of the ash. The low melting temperatures of the rice husk ash may cause bed agglomeration in fluidized bed as well as slagging on surface walls and fouling of heat transfer surfaces [5].

Table 1. Rice husk analysis.

Chemical properties of rice husk	
Moisture	9.0
Proximate analysis (wt% d.b.)	
Volatile matter	63.7
Fixed carbon	10.5
Ash	25.8
Ultimate analysis (wt% d.b.)	
Carbon	45.9
Hydrogen	6.2
Nitrogen	0.6
Oxygen	47.3
HHV (MJ.kg^{-1})	15.7
LHV (MJ.kg^{-1})	14.4
Bulk density (kg.m^{-3})	120

Table 2. Rice husk ash analysis.

Components	**%**
SiO_2	94.81
K_2O	2.99
CaO	0.74
P_2O_5	0.51
Fe_2O_3	0.26
MgO	0.15
Cr_2O_3	0.05
ZnO	0.02

3.2. Reaction chamber

Pyrolysis Stage

Pyrolysis stage is designed as bubbling fluidized bed. The involved parameters need to be considered are minimum fluidization and terminal settling velocity, internal diameter and height of reaction chamber.

Minimum fluidization velocity: The lower limit of the superficial velocity of the air that will flow through the particle bed was considered from the experiment. During the experiments, the air passed upwards through the fixed bed whilst the pressure drop across the bed increased with superficial velocity. The minimum fluidization velocity was the point of velocity which the pressure drop across the bed started constant as shown in Figure 1.

Terminal settling velocity of the particle: The maximum value of the superficial velocity of air was determined for the bed material depending of the Reynolds number (for 0.4<Re<500) of the particle [6],

$$(d_p\, U_t\, \rho_f) \div \mu = (Ar \div 7.5) \wedge 0.666 \qquad (1)$$

Here: $$Ar = ((d_p \wedge 3)\, \rho_f\, g\, (\rho_s - \rho_f)) \div \mu \wedge 2 \qquad (2)$$

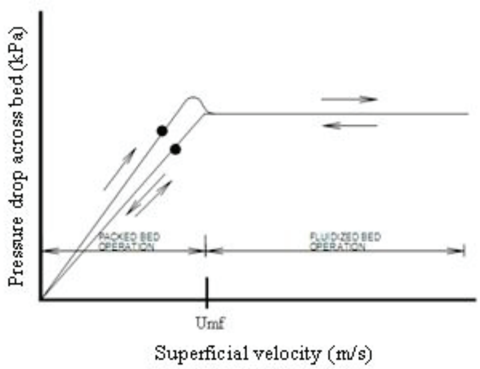

Fig. 1. Relationship between pressure drop across the bed with fluid velocity.

Internal diameter: This parameter depends on the amount of air required. According to the experiment of the effects of ER on the HHV of the producer gas, the ER was changed from 0.16 to 0.26. When the ER was higher than 0.21, the temperature of the combustion zone was higher than 1000 °C. To avoid ash melting problem, the combustion zone temperature has to be controlled below 1100 °C [7]. From these data the ER was determined that this stage is designed for the range of ER from 0.16 to 0.20 by dividing into two parts: upper and lower part.

Height of the reaction chamber: This parameter is determined by the pyrolysis reaction time and calculates the height of the reaction chamber. From the study of effect of pyrolysis reaction time on pyrolysis weight loss [8], the remained char at 700°C at 1 s after injection was found to be as low as 32% of rice husk. This implies that major weight loss could occur during the fast heating period. For longer reaction time, a small additional release of volatile continued by the decrease of char yields at a much slower rate. The design of reactor height and reaction time affects the reactor height. Therefore, to avoid a too-high- reactor, the reaction time is determined as 3 min.

Temperature: From the TGA analysis of rice husk, volatile matters start to leave from rice husk at 200°C and the devolatilization of rice husk completes at 600°C. To remove volatiles remaining in the char as much as possible, the pyrolysis temperature was chosen around 600°C. The design values for pyrolysis stage are shown in Table 3.

Char Gasifer Stage

Char gasifier stage is designed as downdraft gasifier. The parameters have to be considered are internal diameter and height of reaction chamber.

Internal diameter: This parameter is considered from the volume of produced gas and gasification reaction time, and then the internal diameter is calculated. The review of the effect of reaction time on gasification weight loss [8] indicates that volatile matter is rapidly released from the rice husk via primary pyrolysis while the remaining char continues to react with steam progressively yielding the gas products. Little amount of char were found to remain for further reaction during the temperature holding period, since major weight loss occurred immediately after sample was injected into the heated reaction zone. For instance, the char remained at 750°C and 850°C at 1 s after injection were found to be as low as 26 % and 24 % of rice husk, respectively.

Table 3. Design parameters for the pyrolysis stage.

Parameter		**Value**
Minimum fluidization velocity ($m.s^{-1}$)		0.12
Terminal velocity ($m.s^{-1}$)		2.17
Diameter (m)	Upper part	0.09
	Lower part	0.13
Height of reaction chamber (m)	Upper part	0.50
	Lower part	0.50

Table 4. Design parameters for the char gasifier stage.

Parameter		**Value**
Throat Diameter (m)		0.10
Height of reaction chamber (m)	Above the throat	0.70
	Beneath the throat	0.70

Height of the reaction chamber: The height of the char gasifier stage consists of two parts: above and beneath the throat. The important parameters to design the height of char gasifier are the char bed height and the height between beneath the throat and char bed for reducing the temperature from approximately 1000 - 1100°C to less than 800°C to prevent ash melting. With the simulations to investigate the influence of char bed height of rubber wood with an average particle diameter of 3.3 cm on molar percentage of gasification products, calorific value of product gas [9], cold gasification efficiency, exit gas temperature and endothermic heat absorption, the char decreases exponentially with increasing char bed length. The minimum char bed height at which all char get consumed completely is approximately 25 cm. According to the relation of temperature and distance from grate [10], temperature decrease as low as 750 °C at distance of 0.42 m. Table 4 shows the design values for char gasifier stage.

Air Supplied System

There are two parts of air used for a two-stage gasifier. The primary air is supplied for bubbling fluidized bed at the distributor plate, which is designed as a spouted bed type due to its mixing and homogeneous handling of rice husk and silica sand, consisting of a funnel-shape structure through which the air was passed and distributed uniformly into the reactor. This alternative was selected due to its mixing and homogeneous handling of rice husk and silica sand. The secondary air was supplied from the air tuyers placed radially around the circumference of the partial oxidation region. The necessary parameters for the air distribution plate design considered for the most homogeneous material of bed and rice husk can be seen in Table 5.

3.3. The proposed design

It is recognized that the performance of gasifier depends mainly on the equivalence ratio range being used. The lower limit of the range is determined by the minimal amount of air required to oxidize the fuel and generate enough heat to maintain the gasification endothermic reactions. Very small values of the equivalence ratio would reduce the reaction temperature and the energy liberation necessary to maintain the reduction reactions. On the other hand, high equivalence ratios would cause increases the reaction temperature because of the greater amount of oxygen. Figure 2 shows design drawing of the two-stage gasifier.

Table 5. Design parameters for the air distributor plate.

Parameter	Value
Pyrolysis stage	
Fluidization velocity ($m.s^{-1}$)	0.24
Tuyer orifice diameter (m)	0.02
Char gasifier stage	
Tuyer orifice velocity ($m.s^{-1}$)	20
Number of tuyer orifices	6
Tuyer orifice diameter (m)	0.004

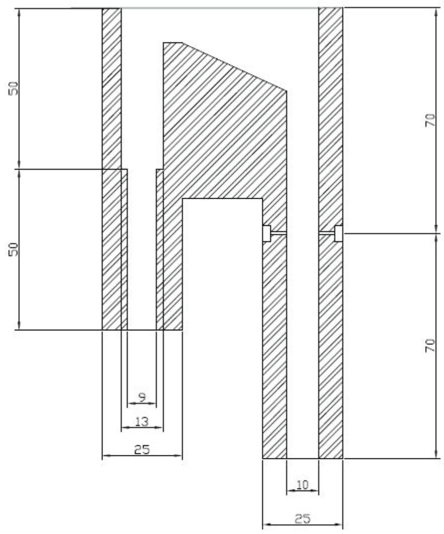

Fig. 2. Design drawing of the two-stage gasifier.

4. Conclusion

Through a simple and practical mathematical model and the experiment, the design of a two-stage gasifier on lab-scale was carried out. The calculated diameters and heights of the lower part and upper part of the first stage were found to be 0.09, 0.13, 0.50, and 0.50 m, respectively. The height of char reduction chamber in the second stage was estimated to be 1.40 m and the calculated diameter was 0.10 m, whereas, the height of the char bed was variable.

The proposed model can be useful when requiring a preliminary prediction of the performance variable values of lab-scale two-stage gasifier. Outcomes from this study can be used to prepare a detail design of a small scale prototype construction. This lab-scale designed is used for estimation of the varying parameters to find out the optimum condition, which can be scaled up in the future.

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