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Industrial demonstration plant for the gasification of herb residue by fluidized bed two-stage process

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HIGHLIGHTS

- A new two-stage gasification process has been proposed to treat biomass.
- The produced tar will be removed effectively by hot char bed layer.
- The pilot test fully verified the feasibility and technical features of the process.

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ABSTRACT

A fluidized bed two-stage gasification process, consisting of a fluidized-bed (FB) pyrolyzer and a transport fluidized bed (TFB) gasifier, has been proposed to gasify biomass for fuel gas production with low tar content. On the basis of our previous fundamental study, an autothermal two-stage gasifier has been designed and built for gasify a kind of Chinese herb residue with a treating capacity of 600 kg/h. The testing data in the operational stable stage of the industrial demonstration plant showed that when keeping the reaction temperatures of pyrolyzer and gasifier respectively at about 700 °C and 850 °C, the heating value of fuel gas can reach 1200 kcal/Nm^3, and the tar content in the produced fuel gas was about 0.4 g/Nm^3. The results from this pilot industrial demonstration plant fully verified the feasibility and technical features of the proposed FB two-stage gasification process.

1. Introduction

Herb residue is a byproduct in Chinese medicine industry after extracting the effective ingredients, which has a production of about 1.5 million tons in China each year (Wang et al., 2010; Guo et al., 2014). Due to the property of high moisture content (about 70%), easy to decay, and lots of drug residues (Yang and Qiu, 2012), the traditional landfill treatment faces serious environmental pollution, such as underwater pollution and the release of smelly gas. On the other hand, characterized by high volatile content, low ash content, ready collection, rich in cellulose and lignin, and having a heating value like some low quality coal, herb residue can be regarded as a renewable energy source (Vandana et al., 2015). So, how to reuse and recycle this kind of biomass resource on the industrial scale effectively and environmentally friendly is a very urgent, significant, yet difficult topic.

Gasification technology is an efficient way for thermochemical utilization of herb residue because of its flexibility and simplicity (Sun et al., 2009). By converting carbonaceous fuel to a combustible gaseous fuel, mainly including CO, H_2, CO_2, CH_4 and C_nH_m, this technology can be widely used in the production of fuel gas for heat and electricity, syngas as raw-material in the manufacture of other value added products, reducing gas for ore roasting and so on (Ahrenfeldt et al., 2013; Duman et al., 2014). Although many reactors can be adopted, such as fixed-bed, moving bed, fluidized bed, entrained flow bed and so on, for fuel gas production, the entrained flow bed gasifier is rarely employed due to the property of higher operating temperature, pressure, cost and poorer adaptability to the raw materials with wide particle size distribution (Kirubakaran et al., 2009; Ouadi et al., 2013). Among the updraft, downdraft and crosscurrent draft fixed bed gasifiers, it is worthwhile to mention the downdraft fixed bed gasifier because of the merit of low tar content in the produced fuel gas. Perhaps this is much related to catalytic reforming effect of hot char bed layer on tar-containing fuel gas (Zeng et al., 2014; Guangul et al.,

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2012). However, the obvious disadvantages of the downdraft fixed bed gasifier, such as, difficult in scale up and poor adaptability for the powder raw material, still limits its application in larger scale (Yu et al., 2015; Asadullah, 2014). Fluidized bed gasifier, including bubbling fluidized bed gasifier, circulating fluidized bed gasifier, and dual fluidized bed gasifier, is more attractive and economical for fuel gas production, due to the advantages of large treatment capacity, wider particle size distribution for solid fuels (below 10 mm), low capital investment and so on. However, the higher tar content in fuel gas produced in FB gasifier is still a great challenge (Kern et al., 2013; Gilbert et al., 2009). At temperature below 300 °C, tar will be condensed and thus cause many operational problems, such as blocking and erosion of equipment and pipeline, deactivation of catalyst, and secondary pollution of phenol-containing wastewater and so on (Li et al., 2015; Shen and Yoshikawa, 2013; Tursun et al., 2015; Sun et al., 2011). So the development of a novel gasifier for biomass with the property of large scale, good adaptability for powder raw material, and low tar content in the produced gas, will become very meaningful and essential.

In this context, a new fluidized bed two-stage gasification process for biomass has been proposed by the Institute of Process Engineering (IPE), Chinese Academy of Sciences (CAS), which mainly consists of a fluidized bed pyrolyzer and transport fluidized bed (TFB) gasifier. Firstly, biomass is pyrolyzed autothermally or oxidized partially in the FB pyrolyzer. Then, all the products from the FB pyrolyzer, including pyrolysis gas, tar, and char, are blown into the downstream transport fluidized bed gasifier to conduct char gasification and pyrolysis gas upgrading. In gasifier, by thermal cracking, partial oxidization, and especial the catalytic reforming from char, the tar will be removed as far as possible during passing through the hot char bed layer. Due to integrating the advantages of FB and TFB reactors (Matsuoka et al., 2013), decoupling the gasification process of biomass gasification into biomass pyrolysis and char gasification (Song et al., 2015), and utilizing the catalytic reforming of char on tar (Zhang et al., 2013; Sonoyama et al., 2011; Nzihou et al., 2013), the new fluidized bed two stage gasification process is not only applicable to powder feedstock (below 10 mm) but also allows rather large treatment capacity and low tar content.

Although there are lots of studies about biomass gasification in literatures, most of these systems were operated at a laboratory scale, and the study about herb residue was also very rare. In this study, firstly, a TGA was used to examine the pyrolysis behavior of herb residue. Subsequently, a pilot industrial-scale gasifier with a treating capacity of 600 kg/h for herb residue was used to evaluate the effect of gasification performance of herb residue on the terms of gas composition, heating value, tar content in the produced fuel gas and so on. The results in this study will be used to guide the design and scale up of the fluidized bed two-stage gasification process.

2. Experimental section

2.1. Fuel and bed material

The herb residue adopted in this study was from a Chinese medicine company located in Henan Province of China, whose lower heating value was about 16.37 MJ/kg. The contents of moisture, ash, volatile matter and fixed carbon were 14.12%, 4.32%, 66.98% and 14.58% on the air-dried basis, while the contents of carbon, hydrogen, sulfur, oxygen, and nitrogen were 51.64%, 5.60%, 0.16%, 41.22% and 1.38% on the dry and ash-free basis, respectively. From it, one can see clearly that the contents of volatile and H were very high, while that of ash was relatively low, indicating a good raw material for gasification. Before experiments conducted on the pilot plant, the herb residue was pretreated by mechanical dewatering, crushing and drying process, decreasing the moisture from 70% to 15%. The particle size distribution of herb residue entered the gasifier was relatively wide, from 0 to 4 mm. Among them, the particle size below 1.0 mm and above 3 mm accounted for about 67% and 8.4%. During experiments, silica sand was adopted as bed material because of its good performance on abrasive resistance, which had a particle size range of 0.2–0.4 mm with a particle density of 2100 kg/Nm^3.

2.2. TGA experimental setup

The non-isothermal pyrolysis of herb residue with different particle size was conducted on an advanced TGA (Nano S II 6300). The biomass sample in platinum crucible was firstly heated at the heating rate of 10 °C/min and kept at 105 °C for 10 min to drive off its moisture. During this period, the carrier gas of nitrogen was introduced at a flow rate of 500 NmL/min. Then a heating rate of 30 °C/min was adopted to heat the biomass sample. The reaction lasted until the weight loss of the sample was no longer decreasing. From the DTG curve presented in TGA, it is very easy to examine the effect of temperature on the property of biomass pyrolysis.

2.3. Pilot scale fluidized bed gasification system

As is sketched in Fig. 1, the fluidized bed two-stage pilot plant was mainly composed of a feeding system, a gas supplying system, a FB pyrolyzer, a TFB gasifier, a gas–solid separating system, a ash removal system, a loop seal, a heat-exchanging system, a boiler and a measuring and control system The pilot plant had a feedstock capacity between 400 and 700 kg/h, depending on the type of fuel and the water content, whose total height was about 17 m. The FB reactor was cuboid structure, having an effective cross-section of about 0.3 m^2 and a height of 1.2 m, while the TFB reactor was column structure, with a cross-section of about 0.25 m^2 and a height of 13 m. An overflow pipe was used to connect the FB and TFB reactors. The primary and secondary heat exchangers were used to preheat the air introduced into the gasifier and pyrolyzer, respectively. An ash removal apparatus was equipped at the bottom of the gasifier, enabling the ash discharge easily. A control and data acquisition system was equipped to automatically monitor the main operating parameters (such as temperature, pressure, gas volume flow, feeding rate of biomass and so on) and the evaluation of the process performance. Downstream the secondary heat exchanger, a tar and gas sampling system was connected on the gas pipeline, consisting of cooling unit, gas cleaning and drying unit, and gas metering unit.

2.4. The experimental procedures

In operation, the start-up of the pyrolyzer and gasifier were firstly heated by burning woody char to raise their temperatures to a required value, which usually lasted about 3 h. At this point, the gasification agent (air, if necessary steam or enriched oxygen) was introduced into the pyrolyzer and gasifier, and regularly regulated to ensure a good fluidization for the bed particles and obtain the desired value of the equivalence ratio (ER). Actually, for pyrolyzer, a little of steam was only adopted at temperature above 720 °C. Then, the herb residue was in turn fed into the pyrolyzer through the screw feeder at a gradually increased rate to maintain and also raise further the temperature. The produced char, pyrolysis gas and gaseous tar in the pyrolyzer were conveyed into the downstream gasifier to form a char bed layer. Meanwhile, the measurements of pressure, temperature, gas flow were performed. Under the required operating conditions of ER and air preheating