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Multi-stage biomass gasification in Internally Circulating Fluidized-bed Gasifier (ICFG): Test operation of animal-waste-derived biomass and parametric investigation at low temperature

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ABSTRACT

In this study, the design, construction and operation of an Internally Circulating Fluidized-bed Gasifier (ICFG) are introduced in detail. ICFG design provides a multi-stage gasification process, with bed material acting as the medium for char combustion and heat exchange by its internal circulation. And it is used for the steam gasification of animal waste at low temperature in view of producing fuel gas. The effects of pressure balance, pyrolysis temperature, catalytic temperature and steam/feedstock ratio on the gasifier performance (e.g. product gas yield, gas composition, tar content) are also discussed. Hydrogen-rich and low-tar product gas can be produced from the low-calorific feedstock, in the properly designed process together with high-performance catalyst.

1. Introduction

Waste production is a very important problem in all countries especially in developed countries. Manure and other animal wastes are unavoidable low valued byproduct of livestock feedlots. Composting process was available to make it as excellent organic fertilizer and soil amendment before, but nowadays, it exceeds about 97 million tons annually in Japan [1]. It is much more than the actual need and results in some environmental problems, such as surface or ground water contamination and air pollution problems with the release of CH_4 (a greenhouse gas), NH_3, H_2S, amides, volatile organic acids, mercaptans, esters, and other compounds [2]. Therefore, environmentally proper method of disposing animal waste is needed, because of the environmental pollution, the regulatory constraints, and more and more expensive landfill disposal.

With respect to global issues of sustainable energy and reduction in greenhouse gases, biomass is getting increased attention as a potential source of renewable energy. The use of biomass as an energy resource would lead to decrease the emission of CO_2, NO_x, SO_x, and particulate matters into the atmosphere [3]. Currently, as one kind of biomass fuel, different technologies like co-combustion of animal waste and coal in boilers, can be used to reduce the dependence on fossil fuels and reduce greenhouse gas emissions [4]. However, the low-energy, high-ash, and high-moisture content of animal waste make gasification an attractive technology [5]. Gasification in fluidized bed offers great advantages to the solid waste treatment and is being used extensively for various biomass fuels [6–12]. In addition, energy efficiency and necessary heat input need to be paid more attention to due to its low-calorific value of the special biomass feedstock. Therefore, low temperature gasification is an interesting alternative, both from the energy point of view [13,14], and to avoid the ash-related problem at high temperature, such as sintering, agglomeration, deposition, erosion and corrosion [11]. When the process is carried out at lower temperature to get higher efficiency and easier operation, more tar and char are produced [10]. But this tar can be eliminated by catalytic decomposition [15]. Besides, steam gasification is a highly endothermal process and needs heat. This heat can be provided by burning the char in a separate chamber and carrying such heat to the gasification with a medium like silica sand [16], which is the origin of the Internally Circulating Fluidized-bed Gasifier (ICFG) design.

2. ICFG design concept

Reactor design is very crucial for gasification in terms of efficiency, heat value of the product gas and also for tar formation [17]. Basically, gasifiers can be categorized in several reactor design groups such as 'single-stage' and 'multi-stage' arrangement [18]. To improve the gasification process, modern and advanced gasification technologies separate the drying, devolatilization, gasification and combustion reaction zones. These 'multi-stage' processes enhance process efficiency and

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product gas quality by combining several reaction zones under consideration of various fuel characteristics. Various 'multi-stage' processes are currently under development or already in operation [18–22]. The high volatile amount of biomass, which is released rapidly as gaseous substances during pyrolysis, is taken into account in numerous reactor concepts by spatial subdivision of the fuel conversion steps. This makes it possible to influence and optimize the operating parameters in each conversion step.

There has been a conceptual design of the Internally Circulating Fluidized-bed Gasifier (ICFG) [23], which has three different functions: gasification, char combustion and bed temperature control. It is composed of two chambers with different specific functions, one is the gasification chamber and the other is the combustion chamber. In each of them, there is a bed material (e.g. silica sand) circulating between these two chambers. Gasification residue including char is transferred from the gasification chamber to combustion chamber by this internal circulation. In the combustion chamber, combustion of char supplies heat to the bed material. The heated bed material is returned to the gasification chamber and supply heat needed for gasification reaction. The design concept is shown in Fig. 1. This kind of gasifier can afford a great diversity of fuels, such as coal, biomass and waste, which seems to be a prospective option for manure compost we concern here.

The concept of that promising gasification process is shared by different researchers and is catching an increasingly greater interest in recent years. Corella et al. [16] gave a thorough review of the relevant gasifiers which existed in the history and are operated today all over the world. After an in-depth and detailed evaluation and analysis of all the available data, the authors presented their doubt about the economical feasibility. For example, external heat supply of energy is necessary to keep the operating temperature of >800 °C because of the highly endothermic gasification with pure steam, and the heat required to generate steam to such temperature. Therefore, relatively low temperature range (600–700 °C) is especially paid attention to and the position of the catalyst bed is also cared in the current paper.

3. Objectives

Previous studies in a lab-scale fluidized-bed reactor have described the gasification characteristics of manure compost and showed that the combination of the high-performance catalyst with the fluidized-bed reactor would provide a suitable system [24]. In addition, Corella et al. [16] mentioned that most reports on ICFG technology were published only in Japanese, making it difficult to report relevant data. Therefore, the main objectives of this study are: (a) to introduce the design and construction of Internally Circulating Fluidized-bed Gasifier (ICFG), and (b) to investigate the feasibility of gasifying manure compost using ICFG, and (c) to evaluate the effects of pressure balance, reaction temperature and steam ratio on the performance of the gasifier.

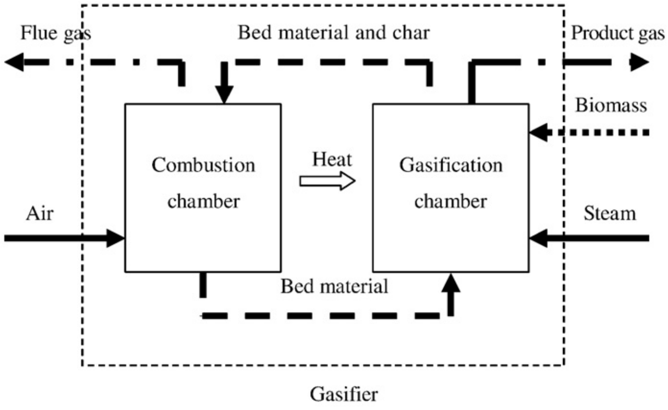

Fig. 1. ICFG concept.

4. Experimental section

4.1. Test facility

The ICFG test facility is an atmospheric installation and consists of six main parts: (1) internally circulating fluidized-bed reactor (core reactor); (2) feedstock feeding section; (3) air and steam supply section; (4) gas cleaning and sampling section; (5) control and data acquisition section; and (6) gas offline/online analysis section. Fig. 2 shows a schematic of ICFG system used in this study. It is designed together with the help and expertise of Ebara Corporation and Suzuki Shoko Co., Ltd. Some technical introduction of this facility has been presented in some recent international conference [25]. With reference to this figure, the following are descriptions of the system components.

4.1.1. Core reactor

The core reactor is made of 6 mm-thick stainless steel with a total height of 1.25 m. An enlarged disengagement section mounted on the top of the main fluidizing part is used to reduce the elutriation rate from the fluidized bed. The height of the enlarged section is 380 mm whereas the bottom and top square cross sections are 212 × 212 mm and 412 × 412 mm, respectively. The angle of inclination is 45° from the vertical axis. In the bottom, perforated plate distributors are used to ensure good gas distribution for a wide range of operating parameters. The reactor is surrounded by three individually controlled electric heating furnaces (10 kW, 7.5 kW and 7.5 kW) that supply heat to keep the desired temperature for different parts during operation. The catalyst bed is settled in the freeboard of the gasification chamber in order to utilize the heat in the reactor for the endothermic reforming reactions and to eliminate the downstream cleanup economically. It is a column container with the inner diameter of 93.6 mm and the height of 320 mm. The catalyst is put inside the catalyst bed, which is operated as a fixed bed.

4.1.2. Feedstock feeding section

It consists of a frame, two hoppers, a stirrer, a screw feeder and a drive system with an electric motor and a speed controller. The frame is designed in such a way that the hopper can slide in and out for easy evaluation and modification. The funnel shaped hopper, which served as a reservoir for the fuel material, has a capacity of about 15 L. The stirrer is used to loosen and mix the fuel, in order to prevent it from settling and consolidating to form a bridge, and to keep the fuel supply homogeneous and consistent. The feedstock is fed by a variable rotating screw feeder (of 25 mm diameter) from the feedstock storage hopper. There is another lock hopper (of 2 L) above it to charge more feedstock for long-time operation, whose principle is similar to solid feeding into pressurized reactors. The compost feed rates are calibrated at different rotating speeds and the maximum can reach about 8 kg/h. The feeding pipe has a water-cooling jacket to avoid feedstock pyrolysis before it enters the gasifier. The feeding point is at 260 mm from the bottom plate.

4.1.3. Air and steam supply section

The air required for both fluidization and combustion is supplied to the combustion chamber by an air supply unit. The unit consists of an air compressor (CFP15-8.5D, Anest Iwata Corporation), an air receiver (AST-120C-140, Anest Iwata Corporation), a pressure gauge having a pressure range of 0–1.0 MPa, a main valve, four rotometers (KOFLOC MODEL RK1200, Kojima Instruments INC.) to control the air flow rates and an air preheater with the capacity of 4 kW.

The water from the water feeding section (including a water tank, a water pump (1M1HA-V0.2F-10D1K, Nikkiso Co., Ltd.), a pressure