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An experimental study on hydrogen enriched gas with reduced tar formation using pre-treated olivine in dual bed steam gasification of mixed biomass compost

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ABSTRACT

The study investigated the effects of pre-treated olivine in dual bed steam gasification (DBSG) of biomass compost in order to produce H_2 enriched synthesis gas with significantly reduced tar formation. The DBSG employed circulating fluidized bed (CFB) of silica sand as first stage and fixed catalytic bed of pre-treated olivine as second stage. The mixed biomass compost contained 15–20 wt. % of agri-residues (mainly wheat straw) and 80–85 wt. % of cow manure. The study compared the synthesis gas distribution and tar reductions using pre-treated olivine in the DBSG scheme with Ni–Al based DBSG scheme. The effects of operating condition on the synthesis gas distribution and tar formation are studied such as: (i) effect of steam to biomass ratio, (ii) effects of relative oxidation (relox), (iii) operating temperature of the reactor, (iv) performance and comparison of employed catalysts, and (v) yield of synthesis gas together with carbon conversion efficiency. Experimental analysis showed that H_2 concentration obtained from pre-treated olivine based DBSG is considerably higher than H_2 produced from compared gasification schemes. The H_2 production is favoured at higher temperatures and higher SBR under the influence of pre-treated olivine catalyst. However, the conditions are less advantageous for the production of CO and CH_4. Among all experiments, the synthesis gas composition obtained at SBR = 1.40 and at 800 °C consisted of highest H_2 concentration (35 vol.% d.n.f) in the pre-treated olivine DBSG. Higher steam to biomass ratio (SBR) resulted in lower cold gas energy efficiency and lower heating value of the synthesis gas mainly due to large steam content in the gas. The tar removal efficiency of 98% is achieved with the pre-treated olivine DBSG system. The total tar content is significantly reduced (≈ 40%) in the DBSG with pre-treated olivine. Higher relative oxidation resulted in increased concentration of CO_2 in the synthesis gas due to increased partial oxidation of organic matter in the gasifier. The pre-treated olivine catalyst in the DBSG consistently promoted the process of steam reforming and tar cracking and thus improved the quality of the syngas by limiting the tar contents.

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Introduction

Background

Renewable energy can play a significant role in order to address climate change issues together with secure energy supply. Agriculture residues and livestock manure represent substantial amount of waste streams in the developing countries that can be used for producing renewable energy. The production of biofuels from such biomass resources can potentially deliver considerable amount of energy and reduce greenhouse gas emissions. The benefits include clean energy supply particularly in the distributed rural areas of developing countries where the energy supply is not adequate. Organic livestock waste and agriculture residues account for more than 60% of total biomass energy resources in the Asian countries, e.g. about 72% of total biomass energy resource in China [1]. Currently, the utilization of such large biomass resource is significantly low, i.e. about 3% [2]. Thermo-chemical technologies for biomass conversion to bio-energy products are considered as efficient methods to produce biofuels for transportation, heat and power production. Biomass gasification, pyrolysis, torrefaction and liquefaction are the most researched thermo-chemical methods [3–7]. However, there are number of issues and barriers in utilizing agriculture residues primarily due to biomass characteristics, e.g. moisture content, silica content, low heating value etc. [8]. The manure composting with or without mixing with agriculture residues represents an alternative waste utilization method for soil amendment [9]. The increasing amount of organic wastes result in environmental issues like ground water contamination, release of methane (CH_4), ammonia and other hazardous compounds contributing to air pollution [10].

Recent research studies revealed the fact that agriculture residues and organic wastes can be used efficiently employing gasification technology to produce biofuels [11]. Gasification and pyrolysis convert such carbon-rich feedstock into a synthesis gas that contains hydrogen (H_2), carbon monoxide (CO) and methane (CH_4) as major constituents [12–16]. The results showed a yield of heavy oil of 40% and high reactivity at highest heating rate due to highly porous structures formed at fast pyrolysis conditions [17,18]. A number of concerted efforts have been made to produce H_2 rich synthesis gas from livestock manure compost and agricultural residues using low, medium and high temperature gasification [19–22]. The catalytic effects of manure compost char and ash on the decomposition of volatiles are determined [23]. The studies on wet livestock manure using supercritical water gasification (hydrothermal gasification) showed that the produced gas constituted water vapour, CO_2, CH_4, N_2 and H_2 [24]. The adiabatic fixed bed gasification of dairy biomass resulted in a product gas consisted of H_2 (13–25%), CO_2 (11–25%), CO (5–12%), CH_4 (0.5–1.8%) and C_2H_6 (0.2-0.7%) [25,26].

Whereas, agriculture residues are primarily composed of cellulose (about 40–50%), hemicellulose (25–35%) and lignin (15–20%) [27–29]. Different types of agricultural residues such as wheat straw, rice straw, rice husk, olive stones, pine shells etc., are experimentally tested in thermo-chemical conversion processes [30–35]. The gasification system employs air, oxygen and steam as the gasifying medium where steam gasification shows better results in fulfilling the heat requirements of endothermic gasification process [36–38].

To avoid tar formation and condensation during biomass gasification (one of the most problematic by-product), the tar removal technologies are characterized into two approaches: (i) treatment inside the gasifiers, and (ii) cleaning of the hot synthesis gas after the gasifier [39–41]. The gasifier performance could be enhanced and tar formation could be reduced considerably using a combination of primary and secondary methods [40]. Although the tar treatments using the secondary methods show competitive results but the primary methods have gained attention due to elimination of tar removal units.

Research question and objective

General research in the area of biomass conversion is on gasification (using air, steam and oxygen as gasifying medium) to produce the synthesis gas with an emphasis on reducing/eliminating tar through primary and secondary methods. However, the dual bed steam gasification (DBSG) with pre-treated olivine as second stage catalytic bed material has not been investigated earlier in order to enhance H_2 concentration in the synthesis gas and reduced tar formation. This study addresses an important research question that:

Can pre-treated olivine as catalyst in the dual bed steam gasification (DBSG) enhance H_2 production with significantly reduced tar formation under different operational conditions?

To address the research question, this study investigates the ability of pre-treated olivine in the DBSG system to reduce considerable tar formation, to increase the hydrogen production and to enhance the synthesis gas yield significantly. The study introduces agriculture residue mixed cow manure compost (15–20 wt. % wheat straw and 80–85 wt. % of manure) to the gasification process. In the DBSG process, biomass is pyrolyzed in a circulating fluidized bed (CFB) of silica sand as first stage and gasification occurred in the second stage fixed catalytic bed. The effects of different catalytic beds ($Ni_2Al_2O_3$ and pre-treated olivine) and operating condition on the synthesis gas distribution and tar formation are studied such as: (i) effect of steam to biomass ratio (SBR), (ii) effects of relative oxidation (Relox) that refers to the ratio of oxygen supplied in the gasifier to oxygen required for complete combustion of biomass, (iii) operating temperature of the reactor, (iv) performance and comparison of introduced catalysts, and (v) the yield of the synthesis gas together with the carbon conversion efficiency and synthesis gas composition. In addition, the overall aim is to promote the distributed bio-energy utilization based on indigenous biomass and waste resources.

Gasification experiments and methodology

Feedstock and bed material

In this study, a mixture of cow manure compost together with indigenous crop residues, i.e. 15–20 wt. % of agri-residues