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Influence of feeding ratio on steam gasification of palm shells in a rotary kiln pilot plant. Experimental and numerical investigations

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ABSTRACT

This paper presents experimental and numerical results on steam gasification of palm shells in a rotary kiln pilot plant. Both the process performance and gas features have been evaluated varying the steam-biomass ratio (SBR), defined as the mass of steam divided by the mass of palm shells. First, some experimental tests have been performed. Then, the obtained experimental results have been used to verify the consistency of a numerical model developed with the aid of the commercial code ChemCAD®.

Numerical results showed that the gas energy content decreases as the SBR increases as well, achieving a maximum value for SBR = 0.6 that produced a gas which volumetric composition N_2 free is H_2 = 40.4%, CO = 24.1%, CO_2 = 21.7%, CH_4 = 12.2%, C_2H_4 = 1.7% and in correspondence of which the lower heating value (LHV) is equal to 12 MJ m^{-3} in normal conditions. SBR values higher than 0.6 do not produce a further increase of the gas yield, rather require a greater amount of input energy for heating the steam from the room temperature to the process temperature.

1. Introduction

Many experts and decision markers agree that many environmental problems will and has occurred because of climate change. According to the Fourth Assessment Report (AR4) of United Nation Intergovernmental Panel on Climate Change (IPPC), released on 17 December 2007, observed global warming over last 50 years is likely due to increase of greenhouse gas emission such as CO_2, coming from the use of fossil fuel and identified as the primary cause of global increment in temperature [1,2]. Thus, the substitution of fossil fuel by renewable energy source appears to be the best and necessary alternative to reduce emission of greenhouse gases and to promote greater energy efficiency. A renewable energy source carried out since antiquity is biomass which can be converted through different physical processes (grinding and drying), biochemical processes (as alcoholic fermentation and anaerobic digestion), and finally thermochemical processes carried out at high temperatures [3–9].

Within the thermochemical procedures three processes can be distinguished, namely combustion, pyrolysis and gasification. Gasification, in particular, is a thermal process that can convert carbonaceous materials, such as organic waste or biomass, into CO and H_2 with a controlled amount of oxidizing agent as oxygen, steam, CO_2 or mix. The resulting gas mixture, also called synthesis gas or syngas, is a fuel able to produce energy (bioenergy) in internal combustion engines, turbines or fuel cells [10–12] or as starting point for the

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Nomenclature

SBR	mass steam divided by mass of palm shells ratio [kg kg^{-1}]
LHV	lower heating value [MJ kg^{-1}]
HHV	higher heating value [MJ kg^{-1}]
t	solid residence time [min]
θ	response angle of matrix [°]
L	length of the kiln [m]
B	correction factor [a dimensional]
S	slope of the kiln [°]
D	kiln diameter [m]
n	angular velocity [min^{-1}]
ΔH_r	reaction enthalpy [kJ kg^{-1}]
T	Temperature [°C]
G	mass flow rate [kg h^{-1}]
P	power from combustion of syngas [kW]

production of chemicals (biofuels) [13]. Steam gasification is one of the promising processes among all biomass conversion ones producing a gas with high H_2 concentration and a ideal [H_2]/[CO] ratio for the synthesis of methanol and Fischer-Tropsch synthesis oil (about 2) [13–18].

This process has several advantages over traditional combustion: a limited formation of dioxins and of nitrous and sulfur oxides; a strong reduction in the process gas volume; production of an energy carrier that can be integrated with combined cycle turbines or reciprocating engines; a reduced amount of secondary wastes; and the possibility to apply the process at a smaller scale [19,20]. On the other hand, during gasification, tars, heavy metals, halogens and alkaline compounds are released within the gas and can cause environmental and operational problems so it is important an improved syngas cleaning, able to meet defined specifications [21–25].

The biomass gasification technology is still not commercialized in full scale but several demonstration plants are under way, and hence studies aimed at developing energy-efficient, economically viable and resource-efficient systems are necessary.

Typically, a gasification plant consists of a gasifier unit, a gas cleaning system and an energy recovery system. Gasification reactors can be basically classified as fixed beds, fluidized beds, rotary kilns or entrained beds.

Rotary kilns has some advantages as good mixing capability, ability to use different materials and efficient heat transfer; the indirect heat rotary meets successfully a bundle of standard gasifier specifications [26], especially for gasifying moist materials [27].

However, the cases of experimental tests of steam gasification of biomass in rotary kiln reactors are not abundant in the literature. They refer basically to the case of steam gasification of lignite briquettes [28], waste wood [29] and poplar [30].

Among all biomass, palm can be a very promising alternative source of renewable energy being the dominant agricultural crop in Malaysia with more than 3.88 million hectares of land under cultivation [31].

Every year, the oil palm industry produces more than one hundred million tonnes of residues worldwide and 1 ha of oil palm plantation can produce about 50–70 tonnes of biomass residues [32,33]. A large quantity of this biomass are generally dumped in open areas, left to rot, or disposed off in open burning, generating pollutant gases [34]. Thus, Malaysia has the potential to be one of the major contributors of renewable energy in the world via palm biomass [35–37]. Some researchers have studied this potential and evaluated the feasibility of biomass power plants in terms of technology availability and economic feasibility [38–41]; the scenario of installing of new Combined Heat and Power plants yielded a number of benefits in terms of net energy savings, net avoided CO_2 emission, and profits [42].

In some cases, palm shells are used as the source of energy for the processing mill itself which produce oil palm to generate heat and electricity via combustion cofiring [43]. However, this is not always practical due to the high moisture content biomass and the huge amount of energy required for complete combustion, thus reducing the energy efficiency. Substantial modification of the furnaces of the mills is needed if the conventional fuel is to be replaced by palm shells.

There are currently no regulations for the management of palm residues except for the general ban on open-air burning as stipulated in 1998 amendments to the Environment Quality Act of 1974. The development of such biomass plants can present an opportunity to produce bioenergy and will have a positive effect on the waste disposal problems faced by various mills, diverting away from incineration and reducing the amount of the residues used as mulch [44].

One advantage would be to enable discarded and/or excess residues for stand-alone power generation via small-scale gasification in the nearby located villages in Malaysia [45].

In spite of the high potential of palm biomass residues too few researches have been published regarding gasification of this material in particular on pilot scale. Within this framework, the current research aims to investigate the gasification of palm shells in a rotary kiln pilot plant. In particular, the influence of the feeding ratio between the gasifying agent (steam) and the material to be gasified on the performance of the process, in terms of amount of gas produced and its composition and content of energy, was examined. The experimental results were compared to an equilibrium simulation model.

2. Experimental work

2.1. *Feedstock and characterization*

The material chosen for experiments has been palm shells, a biomass residue obtained from extraction of the oil palm (*Elaeis guineensis*) from empty fruit bunch coming from the crop of 2011executed in a mill factory in Kuala Langat located in the state of Selangor in Peninsular Malaysia. This process consists of four major steps: sterilization, stripping, screw