Energy 154 (2018) 38–51

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Emissions and performance of a spark-ignition gas engine generator operating with hydrogen-rich syngas, methane and biogas blends for application in southern Brazilian rice industries

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ARTICLE INFO

Article history:
Available online 21 April 2018

Keywords:
Syngas
Methane
Hydrogen
Rice industries
SI
Emission

ABSTRACT

Brazil is one of the world's largest rice producers with more than 50 industries in this field. During the processing of the grain, high amounts of husk are generated, with a capacity to produce synthesis gas with high hydrogen content. On the other hand, in the process of parboiling, the final result is considerable volumes of effluent rich in organic matter, generating high amounts of methane. Therefore, spark ignition engine (SI) can operate with biogas, syngas or biogas-syngas mixtures, taking advantage of the bioenergy potential of the rice industries in Brazil. Accordingly, in this work, it was used the spark-ignition engine test operating with typical biogas and syngas compositions generated in the rice industries, named Bio70, syngas1 and syngas2, respectively. An important result could be observed. For both methane and biogas fuel the increase in excess ratio (λ) value from 1 to 1.25 lead to lower CO and NO_x emissions as well as an increase in indicated efficiency. Using fuel mix, even at low concentration, such as 10% by vol., Bio70 provided increases in the calorific value of air-fuel mixture (e_{dv}) equal to 5.4 and 13.2% for syngas 1 and 2, respectively.

1. Introduction

Currently, in Brazil, the rice (*Oryza sativa*) is one of the most relevant foods for the population's diet and the country is characterized as one of the world's largest producers of cereal [1]. The southern region, more specifically, Rio Grande do Sul state concentrates most of the grain production [2]. As Brazil is the ninth largest rice producer in the world [3], some residues are generated in this food sector, such as husk and effluent, which need to undergo adequate treatment so as not to cause environmental liabilities [4]. For the treatment of effluents, the Upflow Anaerobic Sludge Blanket - UASB reactors are widely used [5], with the consequent production of high amounts of biogas, which encourages the use of the anaerobic digestion. In addition to treatment of effluents it is possible to use the gas generated to energy production, as demonstrated in the country's landfills, for example [6].

In addition to the effluents generated from the biogas, the burning of the rice husks via gasification generates the synthesis gas. Even more than the state of Rio Grande do Sul generates 46% of all the husk produced annually in the country [7], favouring its use for energy purposes [8]. It is important to notice that the common burning process of peels generates highly polluting compounds [9] that are dangerous to human health and the environment [10]. In this sense, the gasification of biomass can minimize this problem [11], especially the gasification of rice husks [12,13], so that process heat can be harnessed industrially, as well as the syngas that can be used to generate thermal energy and electrical in Combined Heat and Power (CHP) systems.

Considering the syngas with the typical composition of rice husks gasification for application in Spark Ignition Engines - SI, no work has been reported in the literature. Generally, the number of studies on the use of synthesis gas from biomass gasification or pyrolysis in SI engines is quite limited and usually concern the gasification of different kinds of woods or seeds.

Furthermore, it was not found any experiment in the literature with mixtures of syngas from rice husks gasification and biogas originated from the anaerobic treatment of rice parboiling effluents. Generally, the papers report only the use of syngas in SI engines [14,15]. Solely one work considering the biogas-syngas mixture was reported, however, the residues used for the

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https://doi.org/10.1016/j.energy.2018.04.046
0360-5442/

Nomenclature

Abbreviations

CO	carbon monoxide
NO_x	nitrogen oxides
HC	hydrocarbon
CO_2	carbon dioxide
H_2	hydrogen
RS	Rio Grande do Sul State
Bio70	biogas with 70% of CH_4 by vol
COV	coefficient of variation
TDC	top dead centre
ECU	Electronic Control Unit
HCNG	hydrogen-enriched compressed natural gas
CH_4	methane
CI	compression ignition
SI	spark ignition
EGR	electricity generation reliability
LHV	lower heating value
KWh	kilowatt hour
AFR	air fuel ratio
IMEP	Indicated Mean Effective Pressure
e_{dv}	lower heating value of air - fuel mixture
CHP	combined Heat and Power

Symbols

p	pressure
t	time
T	temperature
K	Kelvin
η	efficiency
ρ	density
kg	kilogram
%	percentage
Nm^3	normal cubic meter
λ	lambda

production of the originating gases were from horticulture and not rice husks and parboiling effluents [16].

Besides that, it is important to comment, although there are studies that have tested the addition of different levels of hydrogen to methane in SI engines, with reduction of pollutant emissions, improvements in the combustion process and consequent increase in energy conversion efficiency [17], these studies are generally applied to the transportation sector. Wherefore, it is urgent the importance and necessity test mixtures of industrially produced gases, such as biogas and hydrogen-rich syngas and the work of the engine operating with blends between these fuels. Therefore, CHP genset with SI engines operating with biogas or methane-syngas mixtures produced in rice industries can be used to exploit these gases, generating clean and renewable energy, as well as reducing the dependence of the electric energy provided by the grid and mitigate the negative environmental impacts of emissions in the atmosphere.

It is also important to highlight that for established fuels, such as diesel, gasoline and alcohol, aspects related to the energy conversion efficiency of the engine, ignition advance or delay, air/fuel mixtures and their relation to the emission of pollutant gases are widely researched. On the other hand, the use of blends of new fuels in engines, especially biofuels, still needs to be developed, since their use is more recent and not all of the aspects of efficiency and emission are clarified, as well as, due to the rooting of the national oil chain.

Blends with the presence of hydrogen as a fuel for internal combustion engines have many desirable properties, such as flammability limits, minimum ignition energy, high self-ignition temperature and high diffusivity. Generally, studies involving mixtures of methane and hydrogen rely on natural gas as a substitute for methane throughout the experiments. Besides that, no analysis was reported in the literature employing biogas emission and efficiency analysis with typical Brazilian rice industries composition, i.e. 70% methane and 30% CO_2 (Bio70). The present study shows the possibility of using two compositions of Syngas and biogas Bio 70 as well the properties of the mixture as a fuel produced and utilized in SI stationary engines at Brazilian rice industries.

In a study done by Yungjin et al. [18] investigating the effects of CO_2 content in biogas composition on the combustion characteristics and NO_X emissions of an SI engine, the authors found that if the CO_2 concentration increased, the NO_X emissions decreased significantly for all operating conditions and they concluded that a significant reduction in NO_x emissions is expected using biogases containing CO_2.

Another advantage is that using these gases, methane and syngas from rice industries, carbon dioxide emission released from the processes is not considered to be a greenhouse gas emission since the carbon content in the biogas or syngas has a natural origin. The assessment of emissions of biofuels in CHP genset is scarce, especially in the case of rice industries. Growing concerns relate, for example, to NO_x emissions.

The potential of thermal and electric energy production of the parboiling industries of rice in Brazil is high and capable of promoting the energy auto-sufficiency of this food sector, in order to reduce the need to purchase electric energy from the concessionary, besides the possibility of commercialization of the surplus energy. In addition to the energy issue, the targeted use of gases from rice industries contributes to the reduction of emissions of polluting gases, if the industries choose to use them in CHP genset, for example, since this system has the highest efficiency in terms of energy production, when compared to steam turbines, for example.

Accordingly, this research evaluates the work of an experimental system composed of a spark-ignition engine connected to an electric generator and gas analyser. The objective is to verify the aspects related to the emissions of pollutant gases and efficiency of the engine operating with the typical composition of biogas and syngas from rice parboiling industries. The results showed that, if used, the system can be effective for generating heat and electricity locally in these industries.

2. Methodology

2.1. Experimental test rig to emissions and efficiency evaluation

The experiment was carried out on the three cylinders naturally aspirated SI engine. In order to evaluate the efficiency of energy conversion and emission of pollutant gases considering the biofuels and blends, two typical synthesis gas mixtures were composed, denominated Syngas-1 and Syngas-2. As the base fuel, methane was used. In addition, during the experiment, the engine was