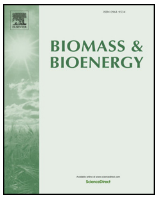
Biomass and Bioenergy 115 (2018) 174–185

Contents lists available at ScienceDirect

Biomass and Bioenergy

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



Research paper

Combustion of fast pyrolysis bio-oil and blends in a micro gas turbine

Marco Buffi[a,b,*], Alessandro Cappelletti[a], Andrea Maria Rizzo[b], Francesco Martelli[a], David Chiaramonti[a,b]

[a] *CREAR, Industrial Engineering Department, University of Florence, Viale Morgagni 40, 50134 Florence, Italy*
[b] *Renewable Energy COnsortium for R&D, RE-CORD c/o University of Florence, Viale J. F. Kennedy, 184, 50038 Pianvallico, Florence, Italy*

ARTICLE INFO

Keywords:
Biofuels
Bioliquids
Fast pyrolysis bio-oil
Gas turbine
Combustion
Emissions

ABSTRACT

The use of Fast Pyrolysis Bio-Oil (FPBO) as fuel was studied in a small scale non-regenerated micro gas turbine, set up in a dedicated test rig. The system includes a dedicated injection line and a modified combustor to burn efficiently high volume fractions of FPBO-in-ethanol solution. The effect of the larger combustor volume improved the quality of the combustion of the reference diesel oil and pure ethanol as regards exhaust emissions, while maintaining unchanged fuel consumptions of the original configuration. Tests with 20/80 and 50/50% (volume fractions) of FPBO/ethanol blends showed successfully and stable engine operation. By increasing the FPBO volume fraction in the fuel blend, an increase in CO emissions was observed - probably due to the larger droplets derived from the more viscous fuel - as well as in NO_X emissions - probably due to fuel-bound nitrogen. Considering the proposed modifications and FPBO/ethanol blend as fuel, the engine reached an overall electrical efficiency higher than that measured with benchmark diesel fuel. A final run with 100% FPBO feeding showed unstable combustion with the presence of carbon deposits in the hot parts of the system, showing that the present configuration requires further modifications to achieve this goal. Guidelines were provided for the implementation of further upgraded solutions for MGTs towards viscous, acidic and aqueous fuels feeding.

1. Introduction

1.1. Fast Pyrolysis Bio-Oil

Bioliquids can substitute part of fossil fuel demand for energy generation. Among these, viscous biocrudes derived from thermochemical processing of lignocellulosic biomass represent an opportunity to store energy and convert it in CHP units. Their use is particularly suited for stationary power generation, since in the energy sector the technology can be adapted to the properties of fuel, reducing the fuel upgrading costs. Differently, the transport sector requires the compliance with specified fuel norms, thus biocrudes and bioliquids must be further processed before their use into existing commercial vehicles, increasing their final cost [1].

In order to feed viscous bioliquids in internal combustion engines and/or gas turbines for small scale CHP units, significant modifications to injection and combustion systems are however required [2,3]. Lignocellulosic-derived bioliquids such as Fast Pyrolysis Bio-Oil (FPBO), show significant differences compared to fossil fuels in terms of chemical and physical properties. A large amount of oxygenated components is present in FPBO: it has a polar nature and cannot be mixed with hydrocarbons. The bio-oil contains water and organic acids, like formic and acetic acid, exhibiting low pH and high TAN (Total Acid Number). The water contained in pyrolysis oil comes from both biomass moisture and reaction stages (process water) [4], the latter including both dehydration and degradation reactions [5]. As regards fuel storage, phase separation typically occurs if the water content in the biocrude is higher than 30–45% [3]. Biomass-derived pyrolysis oil also presents high viscosity compared to fossil liquid fuels, and cannot be heated above 353 K [6–8]. This is a significant difference respect to other bioliquids such as vegetable oils, where the fuel viscosity can be reduced to diesel fuel range just heating above 373 K [9] in order to achieve similar performance compared to conventional fuels [10–12]. Moreover, due to its high oxygen content, pyrolysis oil shows very poor ignition properties and low energy density compared to fossil fuels. An extensive description of fast pyrolysis oil properties and analysis methods has been published by Oasmaa and Peacocke [13]: they provided guidelines in the design of process equipment and power generation systems. Presently, considering commercial applications, two sets of FPBO quality for burners are covered by ASTM D 7544 [14], and the corresponding European standards for boiler FPBO grades are being developed under CEN in the EU [15].

---

[*] Corresponding author. CREAR, Industrial Engineering Department, University of Florence, Viale Morgagni 40, 50134 Florence, Italy.
E-mail address: marco.buffi@unifi.it (M. Buffi).

https://doi.org/10.1016/j.biombioe.2018.04.020
Received 8 October 2017; Received in revised form 20 April 2018; Accepted 24 April 2018

Nomenclature

AC	Alternate current
AFR	Air-Fuel Ratio
APU	Auxiliary Power Unit
ASTM	American Society for Testing and Materials
C	Compressor
CC	Combustion Chamber
CEN	European Committee for Standardization (in French: Comité Européen de Normalisation)
CHNOS	Carbon Hydrogen Nitrogen Oxygen Sulphur (elemental analysis)
CHP	Combined Heat and Power generation
DAQ	Data AcQuisition
DIN	German Institution for Fuel Norms and Specifications (in German: Deutsches Institut für Normung)
EL	Electrical Load
EN	European Norm
ER	Equivalence Ratio
FPBO	Fast Pyrolysis Bio-Oil
GPU	Ground Power Unit
HDPE	High-Density PolyEthylene
HHV	Higher Heating Value
ISO	International Organization for Standardization
LHV	Lower Heating Value
MGT	Micro Gas Turbine
NDIR	Non Dispersive Infra-Red (sensor type)
NDUV	Non Dispersive Ultra-Violet (sensor type)
OC	Original Combustor
ps	Pressure sensor
PO/EtOH	Fast Pyrolysis bio-oil/Ethanol blend
SMD	Sauter Mean Diameter
T	Turbine
TAN	Total Acid Number
Ts	Temperature sensor

1.2. Viscous, acidic fuels in gas turbines

Considering FPBO as fuel for energy generation systems based on internal combustion engines, the main barriers related to its use are the high viscosity and viscosity, and the low heating value. As summarized by Van De Beld et al. [3,16] and other literature on diesel engines [17], significant modifications to the engine are necessary, from fuel storage to the nozzle. A comprehensive overview of the pyrolysis oil use in engines and turbines was given by Chiaramonti et al. [18], that highlighted how corrosion resistant materials, in-line cleaning implementations, and heated feeding lines have to be adapted to operate with the aggressive properties of the biocrude. Czernik and Bridgwater [19] reported a series of experiments on gas turbines which investigated the use of viscous fuels using different methods to accommodate some of the peculiar properties of biomass pyrolysis oils. An advantage of these systems consisted in the "silo" type combustion chamber located outside of the turbo-compressor body, a component that can be easily modified and optimized than annular combustors. This was indeed demonstrated by several researchers from the University of Twente, which studied the effect of vegetable oil [20] and pyrolysis oil [21] in a 50 kW DG4M-1 (electrical power out), a radial design micro gas turbine formerly used as APU. The use of pyrolysis oil and blends was successfully tested and the emissions characterized, showing that pyrolysis oil generates higher CO emissions that other bioliquids. Generally, high CO emissions indicates low combustion efficiency, thus the re-design of combustor becomes crucial. Recently, Beran and Axelsson [22] developed a new concept of combustor able to burn efficiently pyrolysis oil (at full load, from 70 to 100% power) for an OPRA OP16, an all radial single-shaft gas turbine rated at 1.9 MW. Main features of the system are the increased combustor volume to allow the combustion of bioliquids with low energy content, and a dedicated air blast nozzle. They found that the maximum allowed droplet size of the pyrolysis oil spray should be about 50–70% of the droplet size for diesel fuel, to achieve efficient combustion. Other studies and tests on a regenerated small turbine engine were performed by Seljak et al. [23] with the liquefied wood, a biocrude produced from the solvolysis of lignocellulosic biomass in acidified glycols, with fuel properties rather similar to pyrolysis oil. The required MGT adaptations were studied together with the testing methodology and fuel properties [24], leading to the design of an operational prototype [25], tested with different compositions of fuels [26,27]. However, the impeller was operated in absence of an electrical generator, thus requiring further studies to be operated in energy generation applications.

1.3. Aim of the work

The objective of this study is to investigate the operation of a small scale non-regenerated gas turbine when a viscous, acidic and aqueous bioliquid such as FPBO is used as fuel. A gas turbine test rig was developed with several new components that replaced the original ones. The MGT combustor was redesigned, in order achieve higher temperature in the primary combustion zone. Details of the combustor redesign followed previous studies by Cappelletti et al. [28] and more recent developments Beran and Axelsson [22], enlarging the combustion volume to maximize droplets residence times. Previous promising tests on a former version of the MGT test rig with standard fuel (diesel), biodiesel and vegetable oil [29–31], provided evidence that there was still room to improve the system to fast pyrolysis oil feeding. Moreover, other studies on viscous bioliquids in micro gas turbine were carried out on a Capstone C30 LF [32,33], focusing on heating the feeding line above 373 K to reduce oil viscosity and achieve good atomization and a stable combustion for several hours of operation.

Thus, the re-designed MGT rig includes: a new re-designed combustor, two pilot flames for start up/shut down, a new control system, and a new injection line based on a tri-fuel system. A preliminary study on the spray performance was carried out in order to estimate the quality of the atomization. Then, the test campaign evaluated the MGT performance and emissions with reference diesel fuel and ethanol, comparing the original and the new configuration of the combustor (at equal spray performances). The innovative proposal of the work is based on tests with FPBO and ethanol blends at 20/80 and 50/50% (volume fractions).

2. Materials and methods

2.1. Fuel analysis

Five different fuel formulations were considered for MGT tests: pure FPBO, denatured ethanol, two FPBO/ethanol blends at different volume fractions (20/80% and 50/50%), and commercial diesel fuel as benchmark fuel. FPBO was provided by BTG Biomass Technology Group BV (The Netherlands). The bio-oil was obtained by flash pyrolysis of pine wood in a rotating cone reactor at process temperature of 773 K and residence less than 1 s (according to the description of BTG fast pyrolysis reactor [34]). The FPBO is a homogenous liquid with a dark-brown uniform color and no suspended solids, subsequently filtered by BTG in order to reduce the amount of ash and solids, and thus to enable direct applications of the oil on both boilers and gas turbines. The filtered FPBO was sent to Italy and stored in a 1 m^3 HDPE tank, few