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Effects of primary air temperature on emissions of a gas turbine fired by liquefied spruce wood

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ABSTRACT

Innovative lignocellulosic biofuel, obtained through solvolysis of spruce wood in multi-functional alcohols was tested in an experimental turbine engine with different primary air temperatures. Variation of primary air temperature was used to emulate two types of microgas turbine generators – fully recuperated and simple cycle setups resulting in different temperatures of combustion chamber intake air. Results indicate that different temperatures, velocities, and flow conditions in primary zone of combustion chamber strongly influence on droplet penetration depth and rate of mixture formation as well as emissions formation. For the innovative lignocellulosic biofuel emission trends of CO and THC were found to be significantly higher in simple cycle mode, whereas no influence of operation mode was observed for baseline diesel fuel. NO_x emissions of innovative biofuel generally increased in regenerative cycle mode and also became sensitive on turbine inlet temperature, with similar trends being observed with diesel fuel. In the case of innovative fuel, deposits of char and polymerized fuel were observed on the combustor walls after operation in simple cycle mode, whereas in regenerative cycle mode, only small amounts of ash deposits were found on hot path surfaces, indicating beneficial influence of high primary air temperatures on combustion efficiency of innovative fuel.

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1. Introduction

In the search of suitable alternative energy solutions making possible more dispersed and stable future energy production, biofuels are considered as an important long-term pillar of sustainable exploitation of primary resources. 1st generation biofuels are already available on the market for several years now, but they revealed several weaknesses such as

competition with food supply and high initial feedstock price [1]. With this in mind, development of 2nd generation biofuels is still under way and great effort is being put into advancement of fuels from lignocellulosic material. These materials do not interfere with food feedstock and are widely available through wood and leftovers from wood industry. Several procedures were developed to make lignocelluloses suitable for use in current power generating technology and the most

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Abbreviations

w	mass fraction
v	volume fraction
M	molar mass
EQR	equivalence ratio,
sth	stoichiometric ratio
CO	carbon monoxide
THC	total hydrocarbons
NO _x	nitrogen oxides
TIT	turbine inlet temperature
FID	flame ionization detector
CLD	chemiluminescence detector
NDIR	non-dispersive infrared
LW	liquefied wood
D2	no.2 diesel oil
REG	regenerative cycle
SPL	simple cycle
PM	particulate matter
pTSA	para-toluenesulfonic acid

penetrating solutions are presented below to provide that basis for analyses of the investigated fuel.

2nd generation biofuels, namely ethanol, could be obtained through hydrolysis followed by fermentation of lignocellulosic material [1]. Considering that ethanol can only be produced from cellulose fibers (cellulosic ethanol), processes which are able to convert also lignin fraction of the input material are more attractive – these are mainly gasification processes, pyrolysis and different types of liquefaction. One of the options is solvolysis of lignocellulosic materials which requires organic solvent and moderate temperatures (120 °C–250 °C) at atmospheric pressure. Solvents used can be as phenol, acetone and polyhydric alcohols or their mixtures. To optimize the process, several techniques were already investigated to shorten the duration of liquefaction reactions. They include assistance of microwaves [2] or ultrasound [3] and addition of different catalysts i.e. para-toluenesulfonic acid (pTSA) [4] and sulfuric acid [5]. With correctly tuned reaction parameters, liquefaction times could already be as low as 15 min [3].

Fuel, investigated in this article, originates from ultrasonically assisted liquefaction of Norwegian spruce (*Picea abies*) in polyhydric alcohols in the presence of acidic catalyst. In literature, the product is usually named “liquefied wood” (LW) [6,7]. This process was chosen based on the analysis, which considered feedstock availability, reliability as well as costs of the production equipment, which is very important for end-users like industry and local communities. Conversion of lignocellulosic material is very efficient, as 990 g kg⁻¹ of initial material is converted into liquid products when exposed to temperature of 160 °C and atmospheric pressure. High conversion efficiency can also reduce aftertreatment costs, especially on filtration procedure due to low solid residue that requires removal. Polyhydroxy alcohols used in the liquefaction process, were glycerol and di-ethylene glycol. To lower the costs of input material, properly treated residual glycerol from biodiesel production could also be used. Partial

substitution of glycerol with di-ethylene glycol can be performed to reduce the viscosity of the product [8].

In contrast to other thermochemically obtained fuels, i.e. pyrolysis oil or bio-crude (product of hydrothermal liquefaction), the energy demand for this process is fairly low and amounts to 400 J kg⁻¹ [3] with ultrasonic assistance and 7.29 MJ kg⁻¹ without ultrasonic assistance [3]. With ultrasonic assistance liquefaction process is completed in 15 min, whereas without ultrasonic assistance this time increases up to 90 min. Lower calorific value of the product is 20.2 MJ kg⁻¹ and thus only 20 kJ MJ⁻¹ of energy value is consumed for fuel production when ultrasonic assistance is applied. For comparison, production of bio-oil, which has lower calorific value, uses 72 kJ MJ⁻¹ of fuel [9], which equals 1.3 MJ kg⁻¹ for bio-oil with calorific value of 18 MJ kg⁻¹.

Proposal of wood, liquefied in ethylene glycol, upgraded with hydrogenation, for use as a fuel was first time assessed in Refs. [10,11]. Further studies on hydrogenation for fuel purposes were conducted in Ref. [12] with the basic fuel being similar to the one used in the first experimental evaluation of non-upgraded liquefied wood in experimental recuperated microgas turbine (MGT) [13]. This study proved the first evidence on stable combustion of non-upgraded LW. It was also shown that exhaust emissions are strongly dependent on turbine inlet temperature (TIT) and fuel preheat temperature [13]. CO concentration was ranging from 159 to 341 μL L⁻¹ and NO_x from 50 to 76 μL L⁻¹, whereas emissions trends showed different TIT trend compared to those when utilizing diesel fuel (D2) as a reference fuel. Furthermore, two different formulations of LW were tested where it was shown that strong influence of wood content in LW on exhaust emissions is present [14].

Current technology of heat engines on small and medium scale is primarily focused on internal combustion reciprocating engines and gas turbines. Application of LW in piston engines was not considered in this study due to unfavorable physical and chemical characteristics of the LW, i.e. high viscosity, low volatility and high autoignition temperature (Section 2.2 and Ref. [13]). Although fuels with characteristics similar to LW can be utilized in gas turbines featuring external combustion (EFGT), the objectives of this research are aimed to utilization of the LW in directly fired gas turbines with internal combustion. This objective is mainly reasoned by the following facts:

- 1.) utilization of LW in directly fired gas turbines enables very large scalability of the power units as applicable gas turbines cover the range from few tenths kilowatts upward,
- 2.) directly fired gas turbines with internal combustion enable attaining high efficiencies, whereas they can also be coupled with an additional bottoming cycle if production of electric energy is to be maximized,
- 3.) lower specific investment cost in comparison to steam turbine plants.

However, even if EFGT systems utilize high temperature heat exchanger to transfer the heat from flue gas to working medium, their efficiency can still be higher than directly fired systems. This happens in the case of gaseous fuels, provided

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