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# Emissions and Combustion Performance of a Micro Gas Turbine Powered with Liquefied Wood and its Blends

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## Abstract

The combustion of a viscous biofuel, liquefied wood (LW) produced via solvolysis of lignocellulosic biomass in acidified glycols, has been studied in a small gas turbine rig. The test rig includes a modified injection line which is compatible with acidic, viscous biofuels allowing fuel preheating and two pilot injectors, and a re-designed combustion chamber. The link between fuel properties and combustion performance of liquefied wood is investigated by burning the biofuel at different blending ratios with ethanol. Exhaust emissions have been compared to reference measurements with diesel fuel and ethanol. Combustion analysis is supported by the investigation of the engine operating parameters and the main emission species at different electrical loads. The experimental study reveals that it is possible to establish efficient operation of the micro gas turbine while utilizing liquefied wood-ethanol blends with high share of liquefied wood.

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*Keywords:* Viscous biofuel; Solvolysis; Ethanol; Gas turbine; Emissions; Combustion.

## 1. Introduction

There are already several market available applications of conventional biofuels confirming relatively high maturity of the related production and application technologies. One of most important difference between fossil-derived fuels

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and biofuels is the presence of oxygen in the chemical structure of the fuel. As a first consequence, the heating value is lower, whereas this is counteracted by lower stoichiometric values of oxygenated fuels.

Representatives of this group of fuels are multicomponent mixtures derived from depolymerization and fragmentation reactions of three key biomass building blocks: cellulose, hemicellulose, and lignin [1]. The results are dense, viscous biofuels, with a significant water content and low pH value [2], such as pyrolysis oil, liquefied wood or products of hydrothermal liquefaction. These are also the limiting factors for utilization of such fuels in combustion engines [3,4], as their direct utilization without upgrading is most often not possible [5,6]. One of the most comprehensive development processes on a small turbine engine was performed by Seljak et al with liquefied wood (LW) - product of solvolysis of lignocellulosic biomass in acidified glycols, initially proposed as a fuel in [7]. The fuel features similar properties as biomass pyrolysis oil and therefore requires extensive engine adaptations. The adaptation process was thoroughly described in several studies together with testing methodology and interlinking of several interrelated influences [8], leading to operational prototype [9], capable of firing several highly viscous fuels [10,11].

The innovative contribution of the presented work is therefore elaboration of an alternative approach for obtaining stable combustion of the liquefied wood and its blends in a modified APU-derived small scale turbine. This premier use of LW-EtOH blends in a modified APU-derived small scale turbine is based on targeted adaptation of baseline fuel formulation and consequent blending with ethanol to bring the viscosity down to acceptable levels. Present test rig was built with the aim to minimize the extent of system adaptations. Combustion analysis is supported by the investigation of operating parameters and the main emission species at different electrical loads. Additionally, the analysis includes the benchmarking of the obtained data against basic design fuel (diesel) and pure EtOH. The experimental study reveals that it is possible to establish efficient operation of the micro gas turbine while utilizing LW-EtOH blends with high share of LW.

## 2. Materials and methods

### *2.1. Fuel*

The LW was produced according to the procedure described in [16]. Formulation tested in the present study was therefore produced by adding wood flour from European spruce stem to ethylene glycol, acidified with 3% of methane sulfonic acid. The ratio of wood to ethylene glycol was 1:2. Liquefaction residence time and temperature were 3 h and 180 °C at atmospheric pressure. Solid residue in the range of 2% was later removed through a 50 µm filtration.

Due to its high viscosity, the LW was blended with EtOH to reduce the value under 20 cSt to allow a proper fuel atomization into the combustion chamber. EtOH used for blending with LW is a commercial denatured ethanol at 94% volume fraction. The blends were prepared by blending EtOH in two separate liquefied wood tanks, adding respectively the 25 and 50% in mass. Blends were prepared 1 h before tests and presented uniform and stable behavior without the use of other additives.

### *2.2. Experimental test rig*

The test rig developed by CREAR is based on an overhauled micro gas turbine powering a military auxiliary power unit (APU) produced by AiResearch-Garrett Corporation, model GTP 30-67; the engine was acquired from Avon Aero Supply, Inc. (USA). The atomization principle is a single injector, pressure swirl, with a reverse flow silo combustion chamber. The turbine shaft rotates at fixed rotation speed, approximately 53,000 rpm, with an AC output of 25 kVA, 0.8 pF, 400 Hz, 120/208 Volt. The rig was built as test bench for vegetable oils [12] and fast pyrolysis oil [13] and comprises: engine sub-assembly; multi-fuel injection line; control panel; AC generator. The parts are mounted on a mobile frame in aluminium profiles (as shown in Figure 1).

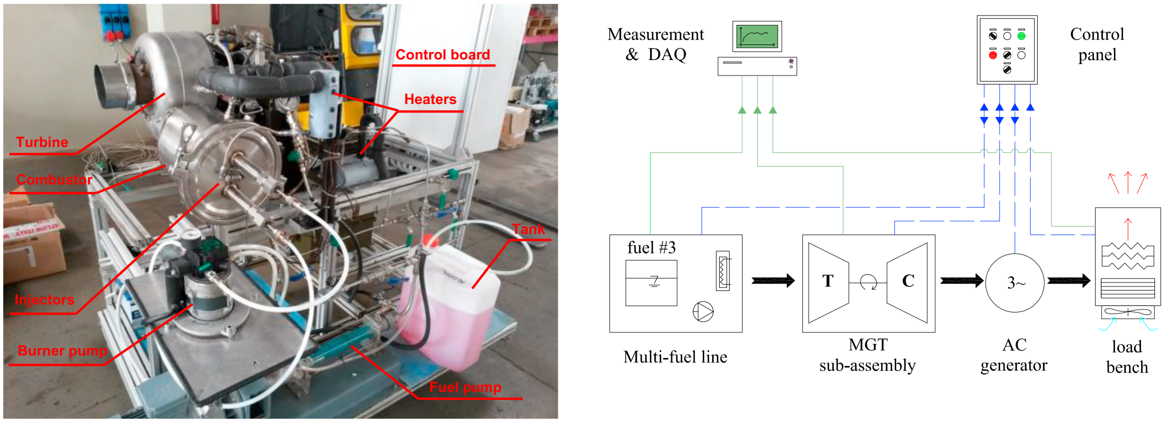

Figure 1: Garrett-AiResearch GTP 30-67 biofuel test bench (right); MGT unit ready for testing (left).

In order to use LW as fuel, the system includes dedicated components making it suitable also for the use of other similar fuels (e.g. fast pyrolysis oil [14]). The original combustion chamber is not able to support successful combustion of low-quality fuels, because of too short residence times, as reported in Cappelletti et al [15]. A combustor was re-designed according to the criteria of Beran et al [16] for pyrolysis oil fueling in gas turbines. The main feature of the re-designed combustor is an increased volume (approximately 4 times than the original one), maintaining the same configuration of the air distribution along the combustion chamber. The re-designed combustor was originally developed to burn efficiently fast pyrolysis oil [13]. Two independent systems for the analysis of exhaust gases concentration were adopted simultaneously. The main one consists of portable on-board exhaust gas analyzer (Sensors Semtech DS) with NDIR method for $CO/CO_2$ measurement, FID for THC measurement and NDUV for $NO/NO_2$ measurement. In parallel, a portable on-line gas analyzer (Greenline 8000), which measures CO, $CO_2$, $O_2$, and $NO_X$ concentrations, performs a double check of the emissions index.

### *2.3. Design of experimental matrix*

The experimental campaign is described in Table 1.

Start-up procedure consists in warming up the engine in idle configuration. Electrical load can be set from 5 to 25 kW, and each measuring point was stabilized for at least 5 minutes before parameter acquisition. When a LW/EtOH blend is tested, the combustion is initially supported by the ethanol pilots. Fuel preheating applied during tests with liquefied wood/ethanol blends was controlled in a way to maintain fuel temperatures at 70°C. The test conditions are summarized in the following Table 1.

Table 1: Experimental plan of the testing campaign.

| **Run** | **Fuel** | **Fuel preheating temperature** | **Electric load** |
|---|---|---|---|
| n | - | [°C] | [kW] |
| 1 | Diesel | 20 | 0, 5, 10, 15, 20 |
| 2 | Ethanol | 70 | 0, 5, 10, 15, 20 |
| 3 | LW-1/EtOH blend 75/25 wt. % | 70 | 20 |
| 4 | LW-1/EtOH blend 50/50 wt. % | 70 | 25 |

## 3. Results

### *3.1. Fuel*

The sample of LW produced via solvolysis of lignocellulosic biomass in ethylene glycol has been chemically investigated in RE-CORD laboratory (Scarperia, Italy) and National Institute of chemistry (Slovenia). The results were reported in Table 2.

Table 2: Chemical characterization of fuels.

| Fuel properties | Unit | Method | Liquefied Wood | Denatured ethanol | LW/EtOH 75/25 wt. % | LW/EtOH 50/50 wt. % |
|---|---|---|---|---|---|---|
| Kinematic viscosity (temperature) | cSt | UNI EN ISO 3104 | > 100<br>(20 °C) | 1.1<br>(20 °C) | 12.24<br>(70 °C) | 14.73<br>(40°C) |
| Density | kg dm$^{-3}$ | UNI EN ISO 3675 | 1.3 | 0.82 | 1.18* | 0.91* |
| Solids content | wt. % | ASTM D7579 | 0.63* | 0 | 0.44 | 0.35* |
| HHV | MJ kg$^{-1}$ | DIN 51900-2 | 25.81 | 25.37 | 25.14 | 25.08 |
| LHV | MJ kg$^{-1}$ | Calculated | 23.93 | 22.76 | 23.06 | 22.8 |

**calculated considering mass fractions*

### 3.2. Gas turbine performance

The effect of fuel composition significantly influenced the combustion performance of the unit (as shown in Table 3). The experiments with blends required the support of pilot flames to ensure a stable combustion. When the engine was fueled by pure blends, pressure and temperature instabilities were observed, and after few seconds the engine shut down. Thus, blends testing was performed by using both pilots flame on. Table 3 shows fuels mass flows for pilots and the main nozzle at 20-25 kW, and consequently the actual LW adopted in combustion was calculated. The engine was operated at stable conditions with 75/25 wt.% LW/EtOH blend at 25 kW (full power) to favor the combustion by reaching the maximum temperature at the exhaust section. A test using a 50/50 wt.% LW/EtOH blend was aimed to test whether operation at part load (20 kW) is possible. This strategy required a second blending ratio with higher share of EtOH to further reduce the viscosity. This test confirmed that the overall combustion efficiency of LW improves for higher thermal power, causing the combustion with 50/50 LW/EtOH blend to be only moderately stable. This two test points thus simultaneously cover two blending ratios and two power outputs – part load and full load which are performed with maximum alowable LW contents for each of the measuring points.

Table 3: Main operative parameters of Garrett GTP 30-67 varying fuel.

| **Effective Power** | **Fuel** | **Injection pressure ratio -Pilots** | **Fuel Flows - pilots** | **Injection pressure ratio - Main Nozzle** | **Fuel flows - main nozzle** | **Actual LW in combustion** | **$O_2$ at exhaust** | **T_ext at outlet** |
|---|---|---|---|---|---|---|---|---|
| kW | | - | kg h$^{-1}$ | - | kg h$^{-1}$ | wt. % | vol. % | °C |
| 19.1 | Diesel fuel | | | 7.60 | 33.00 | | 17.26 | 465 |
| 20 | EtOH | | | 11.60 | 43.00 | | 17.51 | 454 |
| 19 | EtOH (with pilots) | 3.60 | 24.00 | 7.60 | 17.50 | | 17.11 | 425 |
| 24 | LW/EtOH (wt.%) 75/25 | 2.60 | 20.00 | 9.60 | 34.00 | 47.2 | 17.9 | 519 |
| 19.4 | LW/EtOH (wt.%) 50/50 | 2.60 | 24.00 | 7.10 | 15.00 | 19.2 | 17.05 | 458 |

### 3.3. Emissions

I. Benchmark fuel EtOH and diesel fuel.

The CO, HC and $NO_x$ emissions of diesel fuel and ethanol were reported in **Errore. L'origine riferimento non è stata trovata.**, representing the basic emission performance for adapted combustion chamber. The emissions of CO are relatively insensitive to load which is a consequence of high volatility of both fuels, and slightly higher for diesel fuel due to the higher combustion temperature. HC emissions can mostly be attributed to specific flow conditions where low temperatures, combined with low EQR ratios, lead to local extinctions due to over leaning of the mixture (as observed for the EtOH due to its high volatility). Emissions of $NO_x$ are linked to combustion temperature, thus are higher for diesel fuel and increase with the load.

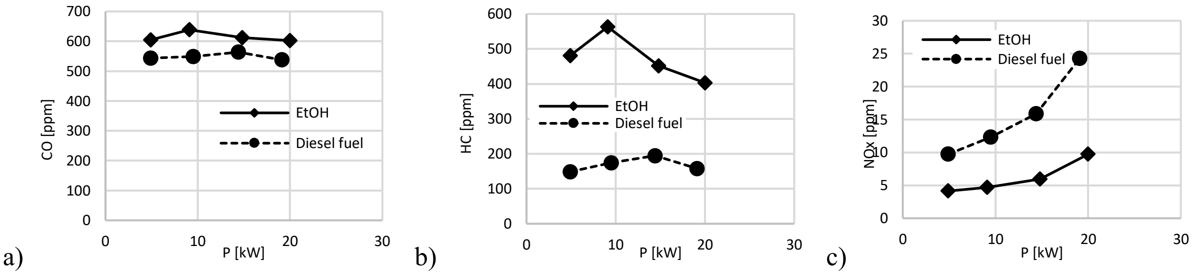

Figure 2: a) CO emissions of EtOH and Diesel. b) HC emissions of EtOH and Diesel. c) $NO_x$ emissions of EtOH and Diesel.

### II. Liquefied wood/EtOH blend

Emissions results in Figure 3 present the operation with LW blends. CO emissions in 3a are almost for an order of magnitude higher than with benchmark fuel in case of both measured points. This general difference is mainly a consequence of density, viscosity and molecular composition of LW blends, provoking larger fuel droplets than diesel fuel. Evaporation rate is further reduced considering the low volatility of LW blend, requiring higher temperatures to minimize the volatile content. Apparently, the LW also exhibits relatively high solid residue after evaporation thus leading to ignition resistant carbon micro-particles, which slowly oxidize very late in the combustion zone.

$NO_x$ emissions for both blends presented in Figure 3b are again notably higher than for benchmark fuel. Such elevation is most likely occurring due to significantly higher nitrogen content in the LW. However, the effect of the higher load for LW/EtOH 75/25 slightly reduce the fuel contribution to $NO_x$ emissions favoring the thermal $NO_x$ formation mechanism.

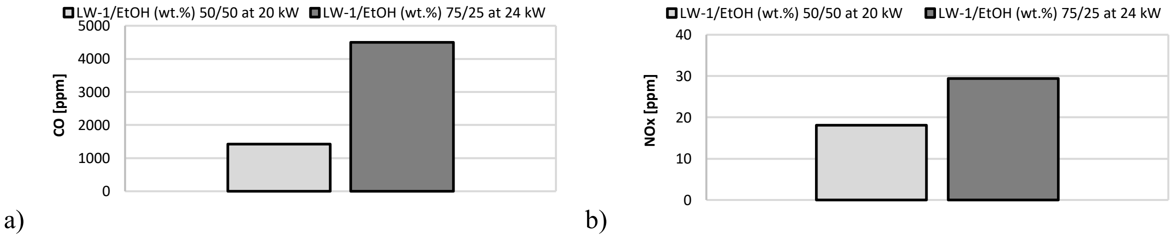

Figure 3: a) CO emissions from blends of LW/EtOH. b) NOx emissions from blends of LW/EtOH

Stability of operation with LW can be preliminary assessed by analyzing time-resolved measurement of emission species. In Figure 4, the switch between benchmark fuel EtOH and LW/EtOH 50/50 blend is presented. At first (570s) the increase in mass flow of EtOH is visible, which was done to accommodate the differences in heating values of the fuel, thus spikes of HC and CO are visible due to the change in the operational regime. After stabilization of operation on EtOH, gradual change of EtOH with LW/EtOH blend is perceivable through elevation of $NO_x$ emissions without significant changes in other emissions, except for gradual increase in CO and HC emissions, which is in line with phenomena described above.

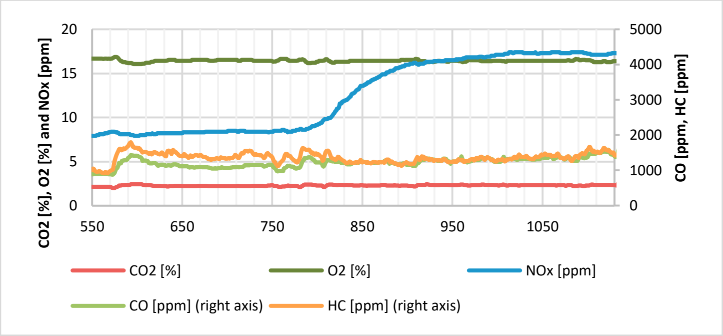

Figure 4: Time resolved emissions during switch between EtOH and LW/EtOH 50/50 blend.

## 4. Conclusions

The innovative contribution of the presented work is the use of liquefied wood-ethanol blends in a modified APU-derived small scale turbine. The configuration of the test rig allowed a premier demonstration of combustion of the liquefied wood/ethanol blends at 75/25 ratio and full load and 50/50 ratio and part load. The emission index revealed that the presence of liquefied wood into the blend significantly affects the CO and $NO_X$ emissions compared to traditional fuels, despite establishing a relatively stable combustion process. In order to reduce the emissions and have a stable combustion by increasing LW content in the blends, advances linked in heat transfer to the droplets would be required to speed up the evaporation process. This can be done by implementing measures which include the elevation of primary combustion air temperature. However, the most significant result revealed that the use of 47.2% of liquefied wood in terms of fuel mass flow in combustion chamber allows to reach a stable combustion at 25 kW power output.

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