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Performance and Emissions of Liquefied Wood as Fuel for a Small Scale Stationary Gas Turbine

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Abstract

This study investigates for the first time the combustion in a micro gas turbine (MGT) of a new bioliquid, a viscous bio-crude which is a liquefied wood produced via solvolysis of lignocellulosic biomass in acidified glycols. The test rig includes a modified fuel injection line, a re-designed combustion chamber and revised fuel injection positions. Thus, the main specific contributions of this paper are: (1) producing of liquefied wood with pure ethylene glycol as a solvent, and methanesulfonic acid as a catalyst, to obtain a bio-crude with lower viscosity and higher lignocellulosics content than previous tested formulations; (2) upgrading raw liquefied wood by blending it with ethanol to further reduce the viscosity of the obtained mixture; (3) utilizing a commercially available MGT Auxiliary Power Unit (APU) of 25kW electrical power output, with notably reduced extent of adaptations to use the newly obtained fuel mixture. Fuel properties and their impact on combustion performance using liquefied wood are investigated by analyzing MGT performance and emissions response at different load and different blend ratios. The experimental study reveals that it is possible to achieve efficient MGT operation while utilizing high biocrude to ethanol ratios, and even reducing the adaptations of the commercial-scale unit to a minimum. The maximum achieved share of liquefied wood in the fuel blend is 47.2% at 25 kW power output. Main barriers to the use of higher share of liquefied wood in these type of systems are also summarized.

Keywords: Bioliquid; Solvolysis; Liquefied wood; Gas turbine; Emissions; Combustion.

1. Introduction

The use of bioliquids as fuel for replacing fossil fuels is particularly interesting for small-scale stationary power generation and CHP. Bioliquids in the form of viscous biocrudes, can partially substitute the fossil sources demand but their use requires significant technology adaptation [1–3]. Differently than biofuels used in transports (such as the low blends of bioethanol and biodiesel), bioliquids as vegetable oils and biocrudes (from thermochemical processing of biomass) can very well fit to the energy sector [4], including decentralized applications. The conversion of the technology to the use of crude bio-based fuels reduces upgrading costs to a minimum.

Among bioliquids, however, vegetable oils compete with food raw materials, so their broad market introduction generated a serious debate about relevant impacts during the entire life cycle as fuels [5]. Non-food derivatives - as liquid biocrudes from thermochemical processing of lignocellulosic biomass - represent a very attractive sustainable opportunity in stationary engines and gas turbines. Bioliquids that fall within this group are multicomponent mixtures derived from depolymerization and fragmentation reactions of the three main building blocks of lignocellulosic biomass, i.e. cellulose, hemicellulose, and lignin [6]. The thermochemical processes available for the conversion of these biomass components mostly yield very viscous products, with high water/oxygen content and low pH value [7]; among these, it is worth to mention fast pyrolysis bio-oil (FPBO), liquefied wood (LW) or products of hydrothermal liquefaction. Their properties are also a limiting factors for utilization of such fuels in combustion engines [2,8], as their direct utilization without upgrading is most often impossible [9,10].

Regarding gas turbine technologies, Lopez et al. [8] tested FPBO in turbomachinery applications. They reported the modifications to the fuel feeding system needed to obtain injection characteristics comparable to those of standard fuels. Andrews et al [11] also carried out some successful tests on the Orenda GT2500, a 2.5 MWe turbine equipped with an experimental dual-fuel nozzle designed to improve spray quality. A recent work reported a successful test with full FPBO feeding a medium-sized (1.9 MW electric power) gas turbine, which was properly modified for this scope [12]. Considering small scale GT units, research on viscous biocrudes in gas turbines was very limited. To the knowledge of the authors, apart from few studies on vegetable oils [13–15] that are not directly comparable to lignocellulosic biomass oils, only two studies tested bio-oil from biomass pyrolysis: Strenziok et al [16] investigated the performance and emissions of an adapted Deuz T216 turbine with 75 kW output; Buffi et al [17] tested a mixture of FPBO/ethanol 50/50 vol.% in the same test rig discussed in this work.

One of the most extensive development of a small-scale gas turbine engine was performed by Seljak et al [18] using LW biocrude, which is the product of solvolysis of lignocellulosic biomass in acidified glycols. This bioliquid features

similar properties as FPBO, and therefore extensive technology modifications are necessary before feeding. The adaptation process was thoroughly described in several studies together with the testing methodology and the interlinkages among several interrelated elements [19], leading to the development of an operational prototype [20], capable of firing several highly viscous fuels (e.g. 68 mPa s at 100°C) [21,22]. These measures are not solely related to the injection system, but rather combines several interventions, in particular:

- implementation of primary air preheating in the range of 400-500°C [23];
- development of pressurized fuel preheating system using suitable components materials [19];
- improved injection nozzle including a thermal insulation to prevent formation of deposits;
- fine tuning of thermodynamic conditions in the combustion chamber [24].

The described solution relies on state of the art technical devices to make the system suitable for high viscosity fuel feeding with the aim to retain the cost advantages of a not-upgraded fuel. The advantage of this approach can be found in the long-term economic return of a MGT setup where the initial investment is higher, but operational costs are reduced due to low fuel price.

The alternative approach to utilize biocrudes in gas turbines designed for conventional hydrocarbons, is to minimize the extent of adaptations on the engine while also reasonably adjust the fuel formulation to comply with the requirements of commercially available units. This approach is more suitable for small throughput quantities and smaller series of engines, as the initial investment in MGT setup is relatively low.

In this paper, this approach is applied to the case of novel formulation of LW. As already discussed, LW is produced via solvolysis of lignocellulosic biomass in multifunctional alcohols. The selection of alcohols was up to now limited to glycerol and diethylene glycol, with the addition of a small amount of acid catalyst (paratoluensulfonic acid). Due to very high viscosity of the LW [21,22], the reduction of fuel viscosity is necessary. The original injection systems, as commonly happens in the majority of stationary gas turbines, accept fuels having viscosities up to 15 mm² s⁻¹ [25] (although some authors suggest even lower values of 12 mm² s⁻¹ [26] or 10 mm² s⁻¹ [27]). Focusing on the LW fuel, the only possible way to reduce the viscosity of LW during the production process is the use of a different solvent. Using ethylene glycol (EG) instead of glycerol (GL) and diethylene glycol (DEG) mixture can significantly reduce the viscosity of the crude LW and at the same time allow for higher blend of lignocellulosic biomass liquid. The viscosity can be further reduced by more conventional measures like blending with ethanol (EtOH), as it is often done with other similar biocrudes (i.e. FPBO). Blending ethanol in a LW formulation with a low molecular weight solvent that favors viscosity reduction, can be considered as a good starting point for successfully operating a commercial MGT, as done for FPBO as fuel in a previous work [17]. The three main specific contributions of the paper that are for the first time evaluated and implemented on laboratory as well as pilot scale can thus be summarized as follows :

- Producing LW with pure EG as solvent, and methanesulfonic acid (MSA) as catalyst, to obtain a low viscosity biocrude at high lignocellulosic content.
- Upgrading raw LW by blending with EtOH to further reduce the viscosity of the mixture.
- Utilizing commercially available MGT setup with notably reduced extent of adaptations than earlier studies to use newly obtained fuel mixture as a fuel.

The main scope and innovative contribution of the present work is therefore the elaboration of an alternative fine-tuned GT-dependent approach to achieve stable combustion of the LW and its blends in a modified APU-derived small scale turbine of 25 kW electrical power out. The test rig, which was built with the aim to minimize the extent of adaptations, includes a fuel preheating system, two additional pilot injectors, and a combustion chamber with larger volume designed for FPBO feeding [17,28–30]. These adaptations can be realized by substituting part of the auxiliary devices of the unit with commercial components thus significantly reducing the level of adaptations compared to previous works. The main component that required a completely new layout was the GT combustor, original designed for conventional hydrocarbon feeding. Combustion analysis is supported by the investigation of the operating parameters and the main emission species at different electrical loads. Additionally, the analysis includes benchmarking data against the original basic design fuel (diesel) and pure EtOH.

2. Materials and methods

2.1. Fuel

The LW biocrude was produced according to the procedure described in [21,22]. From a range of possible formulations yielding different LW properties, those determining the most favorable ones for the use in commercial gas turbines were selected. In particular, the main goal was to produce LW with lowest possible viscosity. During the synthesis, the viscosity of LW can be influenced by three different measures. Firstly, it is related to the content of lignocellulosic material, since the average molecular mass of the product is strongly linked to the content of degradation products of lignocellulosic material. The lower the lignocellulosic biomass, the lower the viscosity of the product. Secondly, viscosity can be limited by using less viscous solvents for liquefaction (i.e. ethylene glycol (EG) instead of glycerol or diethylene glycol). Finally,

viscosity reduction can be achieved by steering the reaction time in a way that limits the production of solid residue and the degree of re-condensation reactions.

The formulation tested in the present study was produced by adding wood flour from European spruce (*Picea abies*) stem to EG, acidified with 2.1 % (in mass) of methane sulfonic acid. The ratio of wood to EG was 1:2. Liquefaction residence time and temperature were 3 h at 180°C at atmospheric pressure. Solid residue in the range of 2% was later separated by filtration at 50 µm. The obtained LW was highly viscous, polar with dark brown to black color [24]. Due to the use of an acid catalyst, the pH value is normally below 3, unless a neutralization step is carried out after liquefaction (which is possible and brings several benefits [22]). The key parameters of the liquefaction process for LW used in the earlier studies [23] and the novel proposed formulation, are summarized in Table 1.

Table 1: Key liquefaction parameters of two LW formulations: previous formulation with DEG/GL; new formulation with EG.

Formulation	LW-DEG/GL	LW (-EG)
-	[wt.%]	[wt.%]
Lignocellulosic biomass	24.4	30
DiEthylene Glycol (DEG)	36.7	0
Glycerol (GL)	36.7	0
Ethylene Glycol (EG)	0	68
Para-Toluensulfonic acid	2.7	0
Methane-sulfonic acid	0	2.1
pH	2.5	2.5
Filtering	50 µm	50 µm
Viscosity*	~250 cSt	~150 cSt

*viscosity measured at 20°C, according to UNI EN ISO 3104 (the grade of uncertainty is due to the fouling of the viscometer capillary).

2.2. Selection of fuel blends

EtOH exhibits good properties as solvent in polar solutions and is widely available as conventional biofuels. LW was blended with EtOH to reduce viscosity below 20 cSt, a figure that should ensure proper fuel atomization in the gas turbine combustion chamber. The EtOH used for blending with LW is a commercial denatured EtOH at 94% volume fraction. Blends were prepared in two separate LW tanks, adding respectively the 25 and 50% (in mass) of EtOH.

Two blend ratios were selected to suit the two tested operating regimes of the MGT, in line with the previous experimental trials using FPBO as fuel [17], suggesting that higher operating load might support operation with fuel with high viscosity, whereas lower load required higher degree of EtOH blending. In line with this assumption, the tested blends were:

- LW/EtOH blend at 75/25 wt.% developed to operate the MGT at full load;
- LW/EtOH blend at 50/50 wt.%, developed to operate the MGT at part load.

The fuel blends were prepared one hour before the tests and kept in a stirred tank. They appeared uniform and stable without the need to use other additives.

2.3. Experimental test rig

The investigation on the micro-gas-turbine (MGT) performance and emissions for the reference fuels (diesel and ethanol) and the selected LW/EtOH blends was carried out in a dedicated rig. It consists in a small power generation unit for testing the combustion of viscous bioliquids. The MGT section is based on an Auxiliary Power Unit (APU) micro gas turbine produced by AiResearch-Garrett Corporation, model GTP 30-67, adapted to power a military ground power unit (GPU), and further reassembled and instrumented in dedicated test rig by RE-CORD. Atomization is performed through a pressure swirl single injector in a reverse flow silo-type combustion chamber. The turbine shaft rotates at a fixed rotational speed of approximately 53,000 rpm, and drives an electrical generator delivering AC at 25 kVA, 0.8 pF, 400 Hz, 120/208 Volt. The rig was designed as a test bench for bioliquids, such as vegetable oils [30] and biomass fast

pyrolysis bio oil [17] and comprises an engine (MGT) sub-assembly, a multi-fuel injection line, a control panel, and the AC generator. Parts are mounted on a mobile aluminum frame as shown in Figure 1.

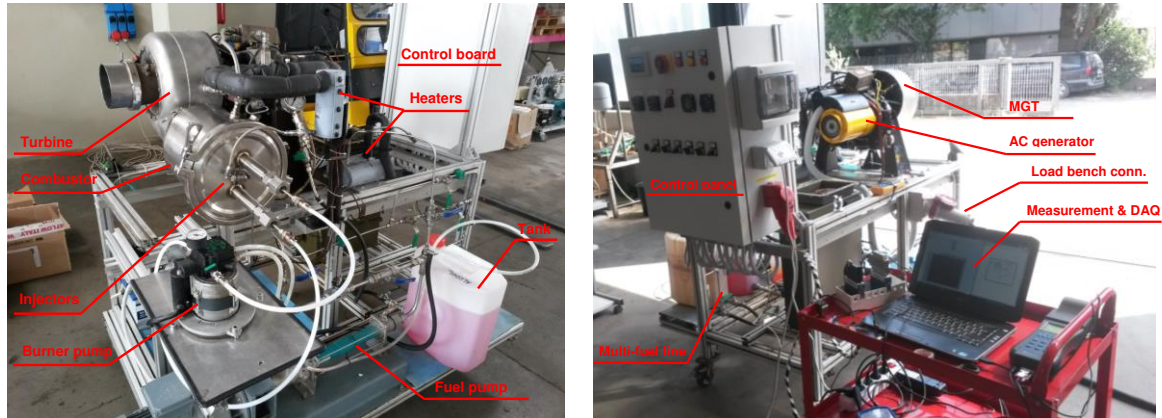


Figure 1: Garrett-AiResearch GTP 30-67 biofuel test bench (left); MGT unit during operation (right).

A load bench then dissipates the electrical power generated by the turbine from 0 to 25 kW. Thanks to its simple and robust radial design, the selected GT technology is relatively easy to operate with a rather broad range of fuels, and the silo-type combustion chamber is easily accessible in case of modifications [30,31].

In order to feed viscous, acidic fuels, the test bench also includes some dedicated components. A screw-type corrosion resistant fuel pump was installed, fully compatible with the very acidic non-lubricating nature of these bioliquids. The injection line is equipped with electric heaters to preheat the fuel up to 100 °C, and two additional pilot injectors were installed for engine warm-up and transient load operations. The original combustion chamber was replaced by a new component which increases the residence time of fuel and combustible gases, as reported by Cappelletti et al [28]. The combustor casing and liner were re-designed based on the criteria given in [17] to allow FPBO combustion, resulting in an increased total volume (~4 times the original) and a similar configuration regarding the air distribution along the combustion chamber than the original model. This set up was adopted for all MGT tests reported in this paper.

2.4. Data acquisition system

Pressure, temperature, power output and fuel flowrate from the MGT test rig were monitored and data collected through a data acquisition system (DAQ) composed by three National Instrument USB modules, supported by the NI c-DAQ 9178 chassis. The installed modules are NI 9401 for digital input/output, NI 9207 for voltage and current measurements, NI 9213 for thermocouple acquisition.

Two independent systems for the analysis of exhaust gases concentration were simultaneously adopted. The main one consists of a portable on-board exhaust gas analyzer (Sensors Semtech-DS) NDIR for CO/CO₂ measurements, FID for THC and NDUV for NO/NO₂. In parallel, a portable on-line gas analyzer (Greenline 8000) measured CO, CO₂, O₂, and NO_x concentrations, to double check the measurements from the Semtech apparatus.

2.5. Modeling the fuel spray

The original Garrett GTP 30-67 injector, based on a pressure swirl nozzle, has been maintained as main injector during the present experimental campaign. Even if other authors suggest different solutions as regards spraying of viscous fuels, as Seljak et al [19,20] and Beran et al [12], the target of this study was the evaluation of the combustion behaviour at equal thermal input with minimum adaptation steps. Considering a longer combustion time due to the revised geometry and increased combustion volume of the combustor, a preliminary investigation of the expected SMD (Sauter Mean Diameter) was carried out. Diesel, EtOH and LW SMDs were evaluated according to Lefebvre [32] through the following equation:

$$SMD = 4,4\sigma^{0,6}\nu_L^{0,16}m_L^{0,22}\Delta P_l^{-0,43}, \quad [1]$$

where σ is the surface tension, ν_L is the kinematic viscosity, m_L is the fuel flow rate and ΔP is the pressure drop over the nozzle. Even if the LW surface tension was not directly measured, previous analysis of biocrudes with similar composition [33,34] suggest that the surface tension is close to those of major multifunctional alcohols used during the liquefaction process: ethylene glycol, diethylene glycol, and glycerol [22,24]. Based on this assumption, the surface tension was

estimated equal to 0.05 kg s^{-2} . The calculations for LW/EtOH blends were carried out by averaging this figure on the base of the masses of the blend components.

In order to verify that similar spray performances of basic design fuel (diesel) can be obtained, spray cone angle and film thickness were also examined. Spray cone angle can be evaluated by a large number correlations, as reported by Lefebvre [35]. The present work used the Giffen and Massey [36] equation of the spray cone half-angle θ :

$$\tan \theta = 0.169 v_L^{-0.131} \quad [2]$$

This equation correlates the spray cone angle to fuel viscosity only. It was chosen since it was already adopted and validated in other similar studies [37–39]. Regarding the film thickness, Rizk and Lefebvre [40] and Suyari and Lefebvre [41] suggested:

$$t = 2.7 \left(\frac{d_0 \dot{m}_L v_L}{\rho_L \Delta P_L} \right)^{0.25} \quad [3]$$

where d_0 is the discharge orifice diameter of the pressure swirl nozzle of Garrett GTP 30-67 (0.75 mm). The present equation was experimentally validated by Kim et al [42], Fu et al [43], Wimmer et al [44] and used in the model of Datta et al [45] for pressure swirl nozzles.

2.6. Design of experiments

The experimental campaign started with a preliminary characterization of the unit with a commercial diesel fuel (EN 590) and pure denatured EtOH. Then, the LW/EtOH blends were tested following a test procedure already developed for FPBO feeding.

The start-up phase consists in warming up the engine at idle conditions (i.e. zero electrical load) for 5 minutes, using diesel fuel. Afterwards, the test rig is ready for experiments with conventional diesel and EtOH. Electrical load can be set from 5 to 25 kW, and each measuring point is stabilized for at least 5 minutes before parameter acquisition. When LW/EtOH blends are tested, fuel combustion is initially supported by EtOH pilot injectors while the main injection line is fed with the tested fuel. In order to maintain constant power out, the EtOH fuel flow of the pilot lines is gradually reduced and the tested fuel flow in the main injection correspondingly increased. The shutdown procedure is the reverse, finally running the GT with diesel fuel to maintain the internal components of the fuel line always lubricated before the shut-off. Fuel preheating of 70°C was always applied when using LW/EtOH blends. The design of experiments is summarized in the following Table 2.

The main operating parameters such as fuel consumption, fuel injection pressure, exhaust temperature, and emissions concentrations were monitored. In particular, the study considered the emissions as an indicator of the efficiency of the combustion process.

Table 2: Experimental plan of the test campaign.

Run	Fuel	Fuel preheating temperature	Electric load
n	-	$[^\circ \text{C}]$	$[\text{kW}]$
1	Diesel	20	0, 5, 10, 15, 20
2	EtOH	70	0, 5, 10, 15, 20
3	LW/EtOH blend 75/25 wt. %	70	20
4	LW/EtOH blend 50/50 wt. %	70	25

2.7. Fuel inspection after MGT tests

When handling the batch of fuel during the experimental trials, the LW/EtOH blend showed an unusual behaviour during blending. Despite LW was previously filtered up to 50 micron, small particles were observed in the internal surface of the storage tanks. In order to attribute the formation of the small particles either to the aging of LW, or to the blending procedure, a short and focused investigation in laboratory was then carried out.

Liquefied wood is a mixture of oxygenated compounds like organic acids, phenolic and alcoholic hydroxyl groups and other polar and non-polar substances [46], which cause a medium level of polarity in the solution and a low pH. In order to dissolve part of the heavy molecular compounds in its composition, solvents can be added to reduce the initial high viscosity of the biocrude. A preliminary investigation of the cold solubility LW in n-hexane, water, ethanol and a methanol-dichloromethane mixture was carried out. The selection of methanol-dichloromethane (1:1 in volume) as solvent was selected following the method developed by Oasmaa and Peacocke [47], i.e. ASTM D7579 to determine the solids content of FPBO.

Solubility tests of pure LW were performed in a 150 mL glass beaker, dosing two drops of LW in the beaker, then adding about 10 ml of solvent. By hand swirling for at least 30 seconds the behavior of the solution was observed. As swirling stopped, the solution was allowed to rest for a moment, then a picture was taken for visual observation.

Moreover, the effect of increasing fuel temperature before atomization in the MGT combustion chamber was investigated. The solubility of ethanol in heavy molecular weight compounds such as waxes and long chain fatty alcohols can be altered by increasing temperature, as studied by Holser and Akin [48]. Thus, the selected blend LW/EtOH 50/50 wt.% was prepared in two separated glass beakers, and the effect of the increasing temperature was visually observed.

3. Results

3.1. Fuel

The sample of LW produced via solvolysis of lignocellulosic biomass in ethylene glycol (EG) was chemically investigated in the RE-CORD laboratory (Scarperia, Italy) and the National Institute of chemistry (Slovenia). Results are reported in Table 3.

Table 3 Chemical characterization of selected fuels.

Fuel properties	Unit	Method	LW	Denatured EtOH	LW/EtOH 75/25 wt. %	LW/EtOH 50/50 wt. %
C	wt. %	ASTM D5291	50.35	44.93	48.99*	47.64*
H	wt. %	ASTM D5291	8.60	12.30	9.52*	10.45*
N	wt. %	ASTM D5291	0.20	0.02	0.15*	0.11*
S	wt. %	Internal method	1.03	0	0.77*	0.51*
Kinematic viscosity (temperature)	cSt	UNI EN ISO 3104	~150 (20 °C)	1.1 (20 °C)	12.24 (70 °C)	5.52 (70°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

The fuel analyses show a significant reduction of viscosity by adding EtOH in LW. The viscosity was reduced below 20 cSt in both LW/EtOH blends, achieving the target to perform a good fuel atomization at the tested conditions in MGT (i.e. injection temperature of 70 °C). The energy content of ethanol is similar to those of LW in mass but, when considering the fuel density, the volumetric energy content significantly reduced by adding EtOH. This measure was relevant to set the proper mass fuel flow in the combustion chamber to maintain the same thermal power during fuel switching. Solids content was measured at 0.44 wt.% for the sample LW/EtOH 75/25 wt.%: this is significantly higher than for FPBO [17], which generally stays below 0.02 wt.% once filtered at the same mesh.

3.2. Fuel atomization and spray

A preliminary cold investigation of the test rig was performed to evaluate fuel mass flows and injection pressure. Then, thermal power was calculated based on the fuel analysis (as given in Table 3). The calculated SMDs [eq. 1] for the investigated fuels are reported in Table 4.

SMD showed slightly higher values for the LW/EtOH blends than for conventional diesel. This result indicated that a pressure-swirl nozzle can be operated with LW as fuel. The higher viscosity of the fuel compared to the design-case of diesel oil can be compensated by increasing pressure drop due to the higher mass flow required by the low LHV of LW to maintain the same thermal input as design-case. Thus, as reported in Equation 1, the surface tension remains the main parameter responsible for the spraying quality. As reported by Beran et al [12] and Shaddix et al [49], the target SMD for viscous, low energy biofuels (such as fast pyrolysis oil) is ~50% of size than diesel fuel. In order to reach this target, the adopted pilot flames were used to compensate the larger size of spray particles and increase the heat rate in the combustion chamber, a solution already proposed by several authors [12,50]. This approach is supported by the positive results obtained with FPBO [17] using the same MGT technology and test bench configuration of the present work. The

investigations on cone angle and film thickness confirmed similar performance for LW/EtOH blends compared to the reference diesel oil. A significant difference was observed in the calculations for pure LW, where the SMD doubled and simultaneously the spray angle significantly reduced compared to the same estimations for diesel fuel. These results confirmed the soundness of the selected strategy of reducing viscosity by adding EtOH-in-LW.

Table 4: Main spray characteristics (calculated).

Fuel	SMD	Half cone angle	Film Thickness
-	$[10^{-5} m]$	<i>Degree</i> $[^{\circ}]$	$[10^{-5} m]$
Diesel fuel	8.11	37.7	4.60
Pure EtOH	5.01	45.6	2.84
LW/EtOH 75/25 wt.%	10.57	36.0	4.49
LW/EtOH 50/50 wt.%	9.93	36.6	5.02
Pure LW	16.00	29.5	7.41

3.3. Gas turbine performance

The effect of fuel composition significantly influenced the combustion performance of the unit (as shown in Table 5). The experiments with LW/EtOH blends required the support of pilot flames to ensure a stable combustion, as previously stated. When the engine was operated without the EtOH pilot flames, pressure and temperature instabilities were observed, resulting in significant variability of exhaust gas emissions. After few seconds, the engine shut down to prevent formation of deposits. Thus, testing of blends was performed by using the two pilot flames (positioned as shown in Figure 2).

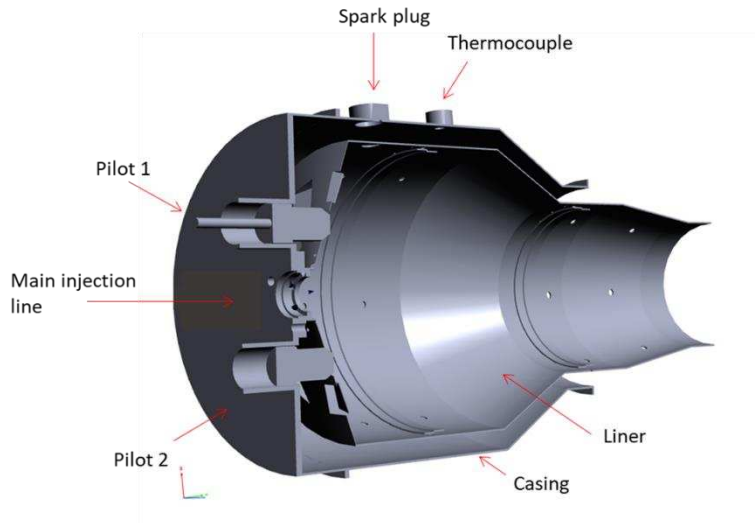


Figure 2: Three-dimensional model of the combustor of the MGT rig.

Table 5 shows fuels mass flows for pilot and main nozzles, and consequently, the actual needed amount of LW was calculated. The GT was operated at stable conditions with a 75/25 wt.% LW/EtOH blend at 25 kW (full power) to favor fuel combustion by reaching the maximum combustion temperature observed by the exhaust temperature measure (as shown by the T_{exh} column parameter in Table 5). Thus, the maximum achieved quantity of LW in combustion was 47.2% of the total mass fuel feed. In order to achieve stable operation also at lower power setting, a 50/50 wt.% LW/EtOH blend was used. The reduced SMD for the 50/50 LW/EtOH test (compared to 75/25 LW/EtOH, as shown in Section 3.2), allowed the operation of the MGT at 20 kW power. However, the actual LW fuel flow was significantly reduced as a consequence of the increased EtOH mass flow through pilot injectors and the higher share of EtOH in the LW/EtOH blend. Thus, the test confirmed that the overall combustion efficiency of LW improves for higher thermal power even though the 50/50 LW/EtOH blend features less demanding physical and chemical properties.

Table 5: Main operative parameters of Garrett GTP 30-67 with tested fuels.

Effective Power	Fuel	Injection pressure ratio - Pilots	Fuel Flow - pilots	Injection pressure ratio - Main Nozzle	Fuel flows - main nozzle	Actual LW in combustion	O ₂ at exhaust	T _{exh} at outlet
<i>kW</i>		-	<i>kg h⁻¹</i>	-	<i>kg h⁻¹</i>	<i>wt. %</i>	<i>vol. %</i>	<i>°C</i>
4.9	Diesel fuel	-	-	5.60	21.00	-	18.40	313.5
9.5	Diesel fuel	-	-	6.60	25.00	-	18.10	359
14.4	Diesel fuel	-	-	7.10	29.00	-	17.81	406
19.1	Diesel fuel	-	-	7.60	33.00	-	17.26	465
4.9	EtOH	-	-	7.60	28.00	-	18.50	307
9.1	EtOH	-	-	8.60	32.00	-	18.10	346
14.8	EtOH	-	-	10.10	37.00	-	17.85	398
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

3.4. Emissions

The emission analysis is first presented for basic design fuel (diesel fuel) and pure EtOH with time-averaged values. This gives an insight into the fundamentals of MGT performance. Similarly, the emissions of LW/EtOH 75/25 and LW/EtOH 50/50 are time-averaged values. Additionally, the LW/EtOH 50/50 is presented also with time-resolved values to provide an insight into the operation stability, which was critical in the case of part load operation.

I. EtOH and diesel

Emissions of diesel fuel represent the basic emission performance of the adapted combustion chamber of the MGT rig, while those using EtOH show the trend with a benchmark fuel. CO emissions are relatively insensitive to the load, which is a consequence of high volatility of both fuels, and competing effects of equivalence ratio (ER) and T_{exh} of the MGT. As T_{exh} increases with the load, an increase in the combustion chamber temperature is observed, which elevates the reaction rates and thus offsets the effect of increasing ER at high T_{exh}. The penalty of a higher ER is thus compensated by the higher TIT (Turbine Inlet Temperature), leading to limited influence of load on CO emissions. Despite the fact that the oxygen content in EtOH aids to reduce local fuel-rich zones, hence decreasing sensitivity of EtOH to global ER ratios, the emissions of EtOH are slightly higher above the entire operating envelop. This fact can be linked to the high volatility of the EtOH, which might cause advection of the mixture to areas with lower temperature, very early in the combustion process, possibly leading to slightly higher CO emissions, as shown in Figure 3.

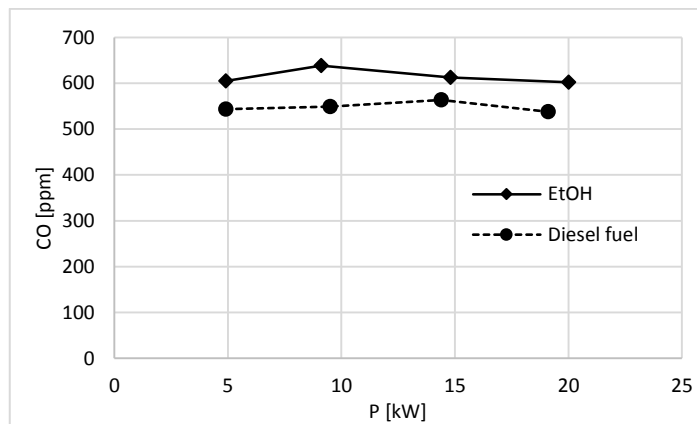


Figure 3: CO emissions of EtOH.

Hydrocarbons (HC) emissions, given in Figure 4, are affected in a similar manner as CO. Although there is no definite trend linked to power output, a slight increase in the emission levels is visible at 10 kW with EtOH, followed by reduction towards high loads with EtOH. Since HC generation is related to local flame extinctions and entrapment of partially

reacted mixture in colder parts of the combustion chamber (i.e. liner cooling air), higher temperatures in the combustion chamber at higher load reduce the occurrence of these phenomena. However, at 10 kW the slight rise in HC emissions can mostly be attributed to specific flow conditions where low temperatures, combined with low ER ratios, lead to local extinctions due to over leaning of the mixture, which is at the same time the consequence of the high volatility of EtOH and suboptimal flame position outside of the recirculation zone. In the case of diesel fuel, these specific flow conditions and the lower volatility of diesel fuel result in shifting of the reaction zone more downstream in the combustion chamber into the primary recirculation zone, decreasing the HC emissions.

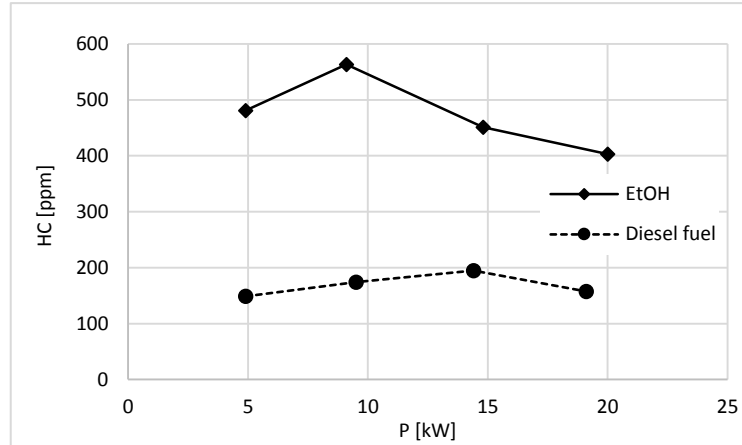


Figure 4: HC emissions of EtOH.

NO_x emissions, shown in in Figure 5, are extremely low for both fuels. This fact can be related to relatively low temperatures in the combustion chamber, which suppress NO_x formation via thermal mechanism, a phenomena that is accelerated at high loads. An additional reason for even lower concentrations using EtOH is the oxygen content present in the alcohol, which produces a combined effect of air reduction and locate combustion enhancement, decreasing nitrogen content in the blend and reducing exposure of OH radicals to nitrogen species, respectively. The improvement of localized combustion efficiency comes with the detrimental effect of an increase amount of HC, as observed in Figure 4. However, regarding NO_x emissions, the lower nitrogen amount reduces the possibility of thermal NO_x formation. The rich side of the flame zone has relatively low temperature and also low nitrogen content, which is followed by relatively fast dilution to lean conditions. This again further limits NO_x formation for EtOH.

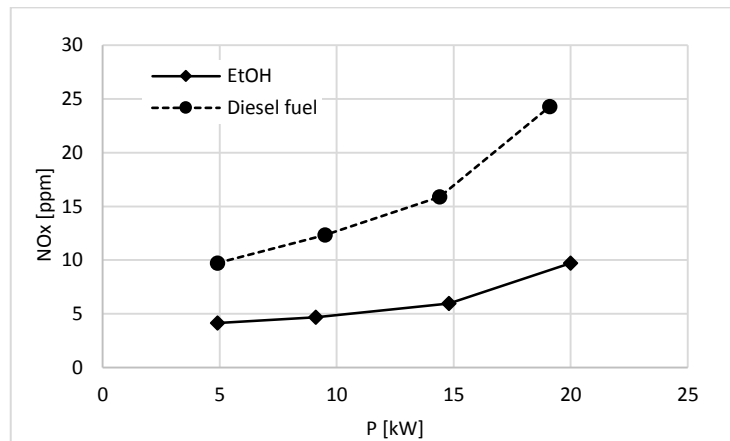


Figure 5: NO_x emissions of EtOH.

II. LW/EtOH blends

Results from the operation of the MGT with LW at two different load points are reported in this section. These operating conditions were selected considering the technical limitations of the experimental setup and the results from previous studies, which suggested that high load operation is necessary to maintain stable combustion. Therefore, the entire load range of MGT was tested only with diesel and EtOH. The first test condition was performed with LW/EtOH

75/25 at full 25 kW power. The second point was set at 20 kW using 50/50 LW/EtOH as fuel. Higher blending ratio are required to obtain stable operation at lower power outputs.

It is evident that CO emissions, shown in Figure 6, are almost one order of magnitude higher than with EtOH in case of both measured points. This difference is mainly due to the density and molecular composition of LW blends, as well as the SMD values, that were roughly estimated ~2-fold larger than for pure EtOH. As indicated above, the density of LW leads to a lower surface-to-mass ratio of the droplets and therefore reduces the evaporation rate of the fuel. Evaporation rate is further reduced considering the low volatility of the LW blends, requiring higher temperatures to minimize the volatile content. LW also exhibits relatively high solid residue after evaporation, thus to the presence of ignition resistant slow-burning carbon micro-particles, which slowly oxidize very late in the combustion zone. LW is markedly multicomponent fuel, containing a wide range of multifunctional alcohols, acids and sugars, requiring wide interval of temperature for the thermal decomposition of the species. Contrary to the single-component EtOH fuel, this fact leads to a relatively long reaction zone, which could extend downstream to the dilution zone of the combustion chamber. All these phenomena strongly contribute to increase CO emissions. If further reduction of CO emissions is required, the implementation of the measures proposed by Seljak et al [20], including the elevation of the primary combustion air temperature by regenerative primary air heating, will be necessary, increasing the technical complexity of MGT adaptations (not the aim of this paper).

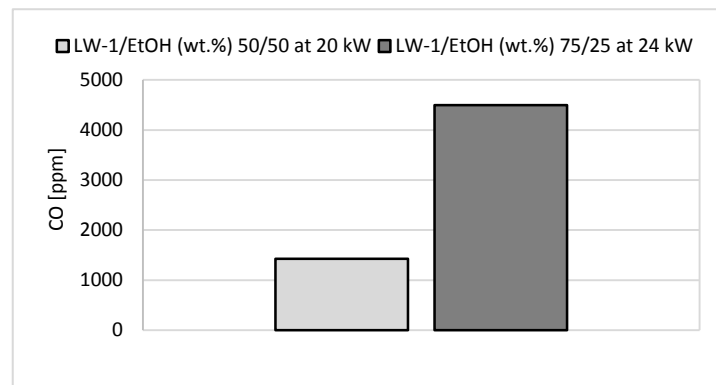


Figure 6: CO emissions from blends of LW/EtOH.

NO_x emissions for both blends are presented in Figure 7: again, these are notably higher than those of the benchmark case. This increase is most likely due to the significantly higher nitrogen content of LW than pure diesel/EtOH (as shown in Table 3). As cited in [22], the conversion of fuel bound nitrogen (FBN) to NO_x in the case of LW is roughly equal to 33%. However, this related to a different experimental setup, with lower ERs and higher temperatures. Also, the rise in NO_x emissions from the LW/EtOH 50/50 compared to the LW/EtOH 75/25 blend can be partly attributed to this phenomena, as LW/EtOH 75/25 has a higher share of fuel-bound nitrogen (FBN) although the load was simultaneously increased, which slightly cover the FBN contribution to NO_x through the thermal NO_x formation mechanism. An important role in NO_x formation is also played by the oxygen content in the fuel, as already discussed for EtOH. The oxygen contained in the fuel reduces the required amount of air while improving combustion, thus the apparent ER on the rich side of the flame is lower, leading to less nitrogen delivered into the flame zone, which reduces the NO_x formation rate.

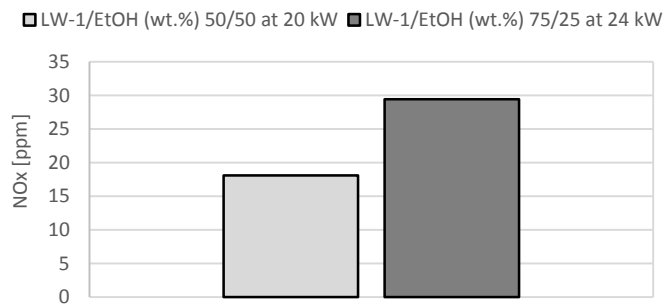


Figure 7: NO_x emissions from blends of LW/EtOH

Stability of operation with LW was preliminarily assessed by analysing time-resolved emission measurements. In Figure 8, the switch between the benchmark fuel EtOH and the LW/EtOH 50/50 blend is presented. At first (570s) the increase in the mass flow of EtOH is visible, which was necessary to balance the differences in fuel heating values, thus peaks of HC and CO are visible due to the change in the operational regime. After stabilization of the operational parameters on EtOH (left part of the Figure 8), the gradual shift from EtOH to LW/EtOH blend is evident, with the increase in the NO_x emissions without a significant change in the other emissions, except for a minor increase in CO and HC emissions, which is in line with our previous discussion. The steady increase in the NO_x emissions is thus mainly a consequence of the increased share of fuel bound nitrogen in the blend, leading to higher NO_x emissions.

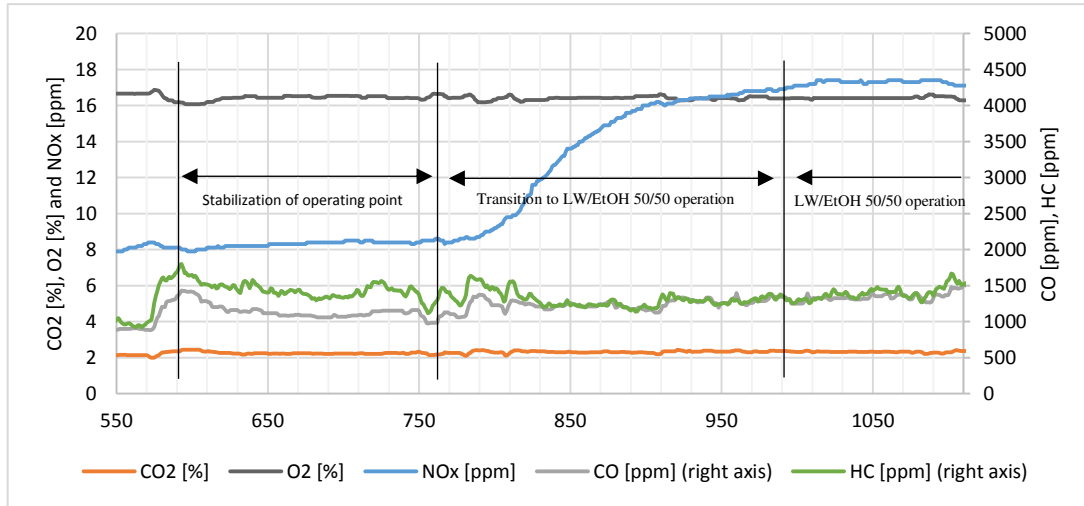


Figure 8: Time resolved emissions during switch between EtOH and LW/EtOH 50/50 blend.

The stability of operation with the LW/EtOH 50/50 blend in the first minutes after switching from EtOH can be considered satisfactory compared to the operation with EtOH. However, long term effects with the LW/EtOH 50/50 and LW/EtOH 75/25 blends reveal that considerable anomalies are present, due to local phenomena occurring in the combustion chamber, in particular during part-load. The most notable one is the occurrence of coke deposits in the walls of the channel that conveys the hot gases from the combustor to the gas turbine impeller, observed in post-test inspection of the hot parts of MGT. Unburned droplets and their slag, which impact and pyrolyze on the internal hot surfaces, were revealed by this effect.

Other observable coke deposits were found on the fuel injection nozzle (as shown in Figure 9). Earlier studies using highly viscous biofuels denote this phenomenon and attributed it to an increased heat transfer rate to the nozzle which happens operating the MGT in regenerative mode, with high primary air temperatures combined with high fuel preheating temperatures. Therefore, it was not possible to maintain the fuel temperature below the estimated point of thermal degradation [51,52]. However, in the present work, the estimated radiative heat transfer to the nozzle was lower compared to the previously cited references, due to low primary air temperature (simple cycle operation) and the lower fuel preheating temperatures. Based on the heat transfer analysis, the main contribution to coking in this case is still the radiative heat transfer, although less extensive than described above. Adopting a pressure swirl atomizer, there is no air thermal barrier between the internal surface of the nozzle and the fuel. Thus, the temperature gain of the relatively thin fuel film in the nozzle can easily exceed the temperature of fuel thermal degradation, causing blockage, off-center spray and significant deposition rate of partly polymerized fuel on internal and external surfaces. This most likely happens even in the case of low primary air temperature as there is small heat resistance through the external layer of the nozzle. This indicates that air-assisted atomizers are not only beneficial for the utilization of fuels with high viscosity, but also for fuels that exhibit low thermal stability.

The tested LW/EtOH 75/25 and LW/EtOH 50/50 blends were developed by targeting the acceptable viscosity for the pressure swirl atomizer, so there should be no need for further adaptation of the injection nozzle. As the fuel exhibits reduced thermal stability [24], thermal protection offered by atomizing air and additional heat capacity of atomizing air can be seen as important features when using biocrudes with poor thermal stability.



Figure 9: Fuel nozzle coking.

3.5. Additional investigation on fuel behavior

Following the MGT testing, the incomplete combustion of LW (due to the relevant presence of deposits) was investigated: additional studies about the properties of fuel were carried out. Despite the technical issues and the limitations already discussed regarding fuel atomization, the present experimental campaign assumed the use of stable and single-phase blend of LW/EtOH. However, during the operations of filling the MGT fuel tank, LW/EtOH showed the presence of small particles and relevant fouling on the internal tank surface. The dark color of the LW, also when mixed with EtOH, does not correspond to a homogeneous blend. In order to understand this phenomenon, attributed to the presence of a solvent (i.e. ethanol) in the fuel mixture, further analyses on the LW solubility were then carried out. Despite the viscosity reduction was achieved by adding ethanol, part of alcohol unreacted species can possibly lead to aggregation/polymerization, and consequently to the formation of particles. The solubility of LW by adding different solvents was studied at lab scale.

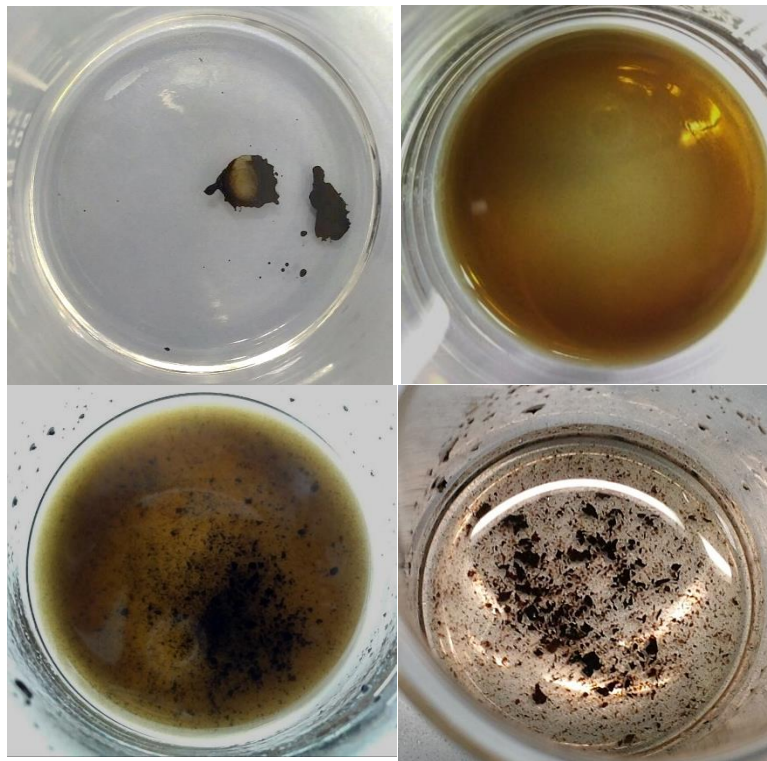


Figure 10: Dissolution tests of LW in four different solvent solutions: (top-left) sample in n-hexane solution; (top-right) sample in methanol-dichloromethane solution; (bottom-left) sample in ethanol solution; (bottom-right) sample in water.

The results of tests (described in section 2.7) of Figure 10 showed that a single solvent (i.e. n-hexane, ethanol and water) is not sufficient to dissolve pure LW: dark insoluble particles were always observed. On the contrary, the solvent composed by a mixture of methanol-dichloromethane (1:1 vol) was the only agent that completely dissolved the solution at visual inspection (Figure 10, top-right image). In order to study the phenomena, the composition of LW was examined: the biocrude is a mixture of molecules with different molecular weights and elemental compositions, and molecules with different functional groups and polarity are present. Thus, a test using a non-polar solvent such as n-hexane expressed a clear immiscibility of the solution, and two distinct phases can be clearly observed (Figure 10, top-left image). Even the use of water (high polar solvent) is not able to solve the LW, causing the presence of a mixture of large particles of LW in water solution (Figure 10, bottom-right image). Ethanol as solvent (Figure 10, top-left image) is able to dissolve a part of the chemical compounds contained in the LW, causing a browner colouring of the solution, but small undissolved particles are still present. Results show that the combination of dichloromethane (i.e. aprotic solvent with an intermediate polarity) and methanol (i.e. protic solvent with high polarity) is the only solvent to exhibit a good solubility in pure LW at macroscopic level.

However, when the LW/EtOH was injected in the combustion chamber of MGT at 70°C, solubility of LW could be altered by the effect of temperature. Figure 11 shows the effect of temperature on the solubility of ethanol-in-LW: as confirmed by the visual observation, after shaking the LW-EtOH samples at ambient temperature, the effect of fouling is significantly higher than samples subject to higher temperature (70 °C). Being the solubility of ethanol increased with temperature, the effect could be more relevant at higher temperature.

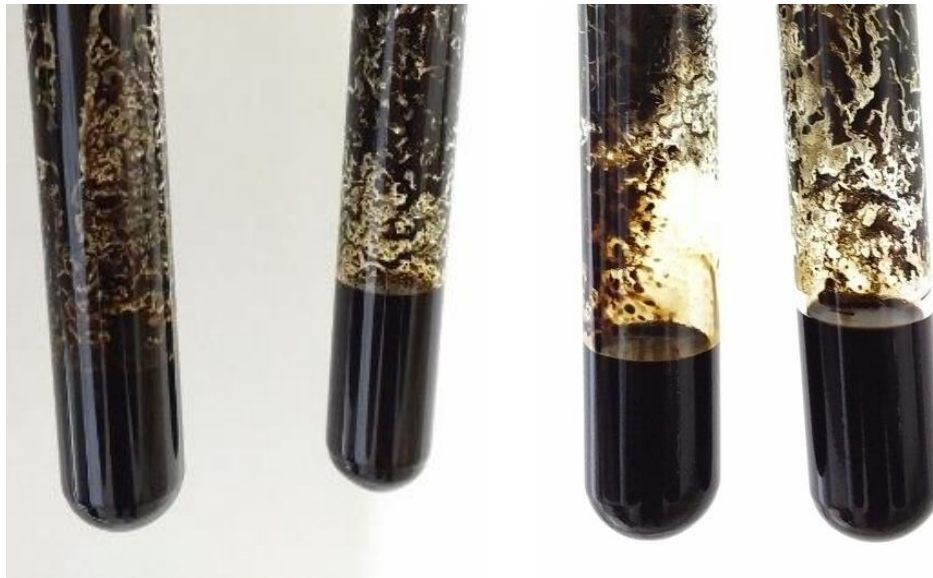


Figure 11: Samples of LW-EtOH (25/75 and 50/50 wt.%) after shaking at ambient temperature (left image). Samples after shaking at 70 °C (right image).

It has been demonstrated that the solubility of LW differs from that of FPBO, which can be easily dissolved in ethanol. The present result enhances the possibility to attribute large part of the observed fuel deposits in the MGT to this effect. Despite fuel preheating favoured the solubility of LW-in-EtOH, two different phases still appear during atomization. Being the fuel blend atomized at this condition, the spray of pure LW droplets requires more time to complete the oxidation process than those of LW dissolved in EtOH. Thus, deposits of char from the pyrolysis of LW droplets are generated and observed during the MGT inspection after test runs.

4. Conclusions

The innovative contribution of the presented work relates to an alternative approach for obtaining stable combustion of an innovative fuel, LW: it represents the first demonstration of the combustion of LW/EtOH in a modified APU-derived small scale turbine. The paper reports also the first analysis of pure LW, produced through biomass liquefaction in ethylene glycol. A significant viscosity reduction for the selected fuel blends was achieved by adding ethanol-in-LW. The maximum achieved share of LW in the fuel in terms of fuel mass flow was 47.2 % at 25 kW power output while at the same time maintaining to a very limited extent MGT adaptations.

The batch of the selected fuels was chemically analyzed, and the SMD estimated. SMD calculations suggested that the mean diameter of LW/EtOH blends droplets is similar to diesel fuel when preheated at 70 °C. The test rig setup allowed to demonstrate the possibility of achieving stable combustion of the LW/EtOH blends at 75/25 and 50/50, and to understand the need for changes in the MGT operating parameters (and emission response) at different electrical loads, comparing them to baseline diesel and pure EtOH as fuels. Emissions revealed that the presence of LW in the blends significantly affects CO and NO_x emissions compared to conventional fuels, despite establishing a relatively stable combustion. In order to increase the flexibility of the MGT in terms of load range, a higher blend ratio is required. In order to avoid this, further investigations on the heat transfer to the fuel droplets will be necessary. Long term operation also revealed that coking on the fuel injection nozzle is a challenge also in simple Joule cycle operation with low primary air temperatures. In terms of heat transfer to the fuel nozzle, the analysis proved that the nozzle can be improved by decreasing the energy transfer towards the incoming fuel, benefiting the formation of droplets whilst reducing blocking by burned solid matter and deposits.

Coke deposits on the channel walls conveying the hot gases from the combustor to the gas turbine impeller were also revealed. This effect was attributed to the incomplete combustion of LW droplets in the combustion chamber. Further laboratory investigations on the fuel properties demonstrated the incomplete solubility of LW-in-EtOH, differently to what happens with other biocrudes such as commercial FPBO.

The present research work suggests that viscosity is not the only property of selected biocrudes that limits their use in MGTs. Solubility, thermal stability and behaviour under rapid heating conditions can be considered as equally important or even more important than viscosity alone. Measures for fuel viscosity reduction are relatively well established, usually relying on blending or preheating, however thermal stability and solubility of the fuel is inherently linked to fuel's molecular structure. These properties should therefore be properly taken into account since the early stage of the design of the MGT system, as fuel upgrading of the fuel is generally one of the few options also in case of stationary power generation applications.

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